

**Simulation for Additive
Manufacturing
2017
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Abstracts

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PREFACE

In the past few years additive manufacturing (AM) has evolved to one of the most promising techniques for creating solid structures of virtually any shape. Yet, AM products and processes are often much more complex than those obtained through classical manufacturing techniques, raising new questions for numerical simulations.

Applications for AM products range across many fields in engineering, from design models to lightweight components for the automotive or aerospace industry, or to medical applications like patient specific implants.

AM processes involve multi-physics and multi-scale phenomena. Whereas relevant spatial scales range over many orders of magnitude, important time scales start at microseconds for physical processes and reach to hours or even days. Physics involved include mechanical, thermal, radiation and phase change problems. And most essential for simulation of AM is validation and verification. Last but not least a lack of appropriate manufacturing technologies hindered for a long time the realization of designs as obtained, e.g. by shape and/or topology optimization. In this regard AM is the ideal technology to transfer innovative design proposals to reality.

This is the first ECCOMAS thematic conference devoted to this subject. Enjoy.

PLENARY TALKS

Developments in Computational Welding Mechanics for Additive Manufacturing

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Approaches developed within computational welding mechanics (CWM) are readily transferable to Direct Energy Deposit (DED) methods [1, 2] whereas Powder Bed Fusion (PBF) processes bring additional challenges to the modelling and simulation, particularly due to the larger amount of thin layers in the process. CWM models focus on the overall behaviour of the component. They usually ignore whatever happens before the weld starts to solidify and thus limits the range of phenomena they can describe. The talk covers the current state of art with particular focus on material modelling in presence of microstructural changes. It will also touch upon techniques for efficient simulations, as more details given in other presentations at the conference. The talk will also describe the current lines of developments towards estimation of defects due to hot cracking for Inconel 718 as well as future work on pore generation in weld zone of Ti 6Al-4V. The latter requires information about the weld pool behaviour bringing additional challenges.

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Topology optimization of structures and infill for additive manufacturing

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Key Words: *Structural optimization, Topology Optimization, Additive Manufacturing, Infill.*

Topology optimization (TO) [1] is a widely used tool for generating optimal structures for subsequent realization by additive manufacturing (AM) methods. TO is a numerical method that, based on iterated finite element analyses, gradient-based optimization algorithms and design parameterizations described by point clouds, delivers optimal but often rather complex topologies. As such, TO is a design method that takes full advantage of the large design freedom offered by AM technologies. Much recent effort in the TO community has been devoted to the development of algorithms that take manufacturing constraints into account, such as overhang angles, printing directions and minimization of support material. In this talk we will discuss recent developments in simultaneous design of structures and their infill.

Infill in AM is often used to save material consumption and weight. Infill is also used as a design gimmick to illustrate the capabilities of AM to mimic natural creations like honeycombs and bone structure. Partly for manufacturing reasons, infill microstructure is often built as open-walled foam structures. However, as maybe unknown by many, open-walled microstructures are not optimal with respect to stiffness [2]. Even if one builds structures with uniform and stiffer closed-walled infill, it does not beat simple solid structures with regards to stiffness. On the other hand, porous infill structures may posses an advantage with regards to buckling stability compared to their solid counterparts [3].

The talk will discuss above issues in more detail and present recent developments with regards to topology optimization with uniform and isotropic infill [3, 4, 5], anisotropic infill for fixed outer geometries [6], simultaneous anisotropic infill and structural design [7], as well as recent developments in multi-scale topology optimization approaches that may speed up the previously mentioned approaches [8].

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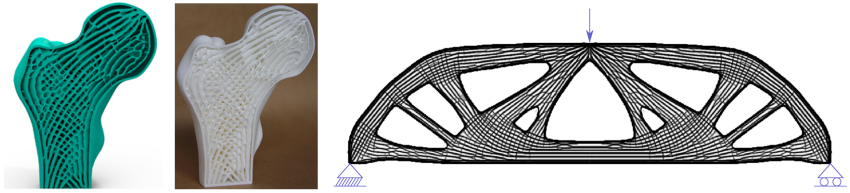


Figure 1: Examples of topology optimization of structures with infill. From [6] (left) and [7] (right).

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Numerical modeling of the AM process by metal deposition and its experimental validation

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Key Words: *Additive Manufacturing, Metal Deposition, Thermo-mechanical modeling, Blown-powder, Wire-feeding, SLM*

In this work the current developments on the numerical simulation of the Additive Manufacturing (AM) processes by Metal Deposition (MD) are presented. A fully coupled thermo-mechanical framework has been tailored to the analysis of both wire-feeding [1] and blown-powder [2] technologies. The accurate definition of the power input is addressed taking into account its actual movement along the scanning path as defined for the machine. The result is a high-fidelity simulation of the metal deposition process leading to an accurate layer-by-layer building sequence. Furthermore, the heat loss by convection and radiation through the boundaries of the computational domain is analyzed taking into account the building sequence during the fabrication process.

An advanced high-performance and object-oriented software platform has been enhanced to include the parallel FE activation technique used to follow the growth of the geometry according to the metal deposition process. The global linear system of equations is preconditioned with the highly scalable implementation of Balancing Domain Decomposition by Constraints (BDDC) in [3]. The weak scalability analysis shows the good performance of this HPC framework for AM simulations.

A thermo-viscoelastic-viscoplastic constitutive model is introduced and characterized for both Ti64 and Inconel-718 super alloys as the reference materials for the fabrication of different components for the aeronautical and aerospace industry. This constitutive model is calibrated and the numerical results are validated through the experimental campaign carried out at State Key Laboratory of Solidification Processing (SKLSP), at the Northwestern Polytechnical University (NPU) in Xi'an (China) as well as at the Department of Mechanical and Aerospace Engineering at the Monash University in Melbourne (Australia).

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Additive manufacturing of metals: an integrated materials approach

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Key Words: *Microstructure Characterization, Residual Stresses, Thermography*

Additive manufacturing (AM) of metal components is a rapidly growing advanced manufacturing paradigm that promises unparalleled flexibility in the production of parts with complex geometries. However, the extreme processing conditions create inhomogeneous materials that can include intense localized compositional gradients, elongated microstructures, highly anisotropic local and macroscopic stresses that approach the flow stress, and unexpected crystalline phases. Substantial post processing is typically required to achieve useable mechanical properties, but position-dependent variations within the part and life-cycle issues such as fatigue and corrosion greatly complicate part qualification. The route to qualification of AM materials requires close control of the build process (including open-architecture instrumentation, design of experiment predictions, in situ process monitoring, and processing feedback loops), world-leading in situ and ex situ characterization and modeling of the as-built and post-processed microstructure [1,2] and stresses, and rigorous characterization and modeling of the in-service environment material behavior [3]. I will describe NIST work on in situ process monitoring, the NIST Additive Manufacturing Metrology Testbed, and material studies of AM alloys such as Inconel 625, ATI 718Plus and 17-4 steel. Finally, I will describe our progress in establishing the Additive Manufacturing Benchmark Test Series (AM-Bench), a continuing series of highly controlled benchmark tests for additive manufacturing that will allow modelers around the world to test their simulations against rigorous, highly controlled AM benchmark test data.

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Innovative material characterization methods supporting structural design of metallic AM parts

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Key Words: *Material testing, Fatigue design, Ti6Al4V, Powder bed fusion, Mini specimens*

Many additive manufacturing (AM) technologies are currently available. Among them, the powder bed fusion (PBF) technology uses a concentrated energy source (i.e. laser or electron beam) to selectively melt, layer after layer, metal alloys powders and thus obtaining parts of complex geometry and with fully functional properties, [1]. High-density metal structures ($\geq 99.7\%$) having static mechanical properties comparable to those of conventional production processes are obtained after process parameter optimization.

The on-going drive for a full exploitation of metal PBF technology by demanding fields such as aerospace, energy, motor racing and medical poses a great challenge to technology providers, end-users and researchers: knowledge aimed at supporting design and qualification of load-bearing metal parts in challenging applications is needed.

Specific features characterize the parts obtained with PBF process and need to be understood: i) the complex microstructure due to the layer-wise production is expected to induce a degree of directionality in the material response; ii) residual stresses are associated to local melting and solidification and to repeated heating and cooling. Therefore post-fabrication heat treatments of the different metal systems are also subject of study and optimization; iii) the surface finish of a PBF part is also a source of study and concern. While static properties are relatively unaffected by the surface characteristics, the response of as-built metals is strongly and negatively affected by dynamic service conditions. While there are many studies of the links between process parameters, microstructure and static mechanical properties of various PBF metals, the information on their fatigue behavior is relatively scarce, [2].

Fatigue testing is typically an expensive activity. Because of the inherent material data scatter, multiple specimens (typically 10 to 20) are required to characterize one material state under a specific test condition. Fatigue testing is therefore time consuming as a test run at a typical frequency of 15 – 50 Hz requires from several hours for short term data to several days to reach high cycle counts (i.e. 2 to 10 million cycles). The PBF technology places a additional burden on fatigue testing as specimens production is costly in terms of material usage (metal powders are very expensive) and AM system usage.

This contribution presents ad-hoc experimental techniques and recent fatigue results developed within the framework of the structural design of metallic PBF parts. The innovative miniature specimen geometry of Fig. 1 has been recently proposed to address all the above negative issues involved in fatigue testing of PBF metals, [3], and to allow the study of the as-built fatigue performance in three material directions unlike the standard specimen. As the specimen unit cost depends on its volume

and the time required for its production, the new specimen allows a cost saving of roughly an order-of-magnitude compared to standard. The mini specimen is loaded in cyclic bending instead of rotating bending but it shares the same reference section properties and therefore size- and loading-type effects are reasonably similar. Fig. 2 demonstrates an interesting feature of the mini specimens: they can be readily oriented on the build plate with their axis oriented in different directions with respect to build.



Fig. 1 Comparison of standard vs. miniature specimens for fatigue testing of AM metals

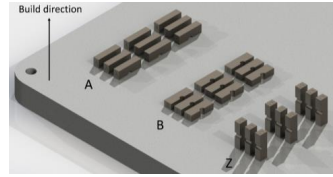


Fig. 2 Different mini specimen orientations with respect to build direction

The testing method based on mini specimens was validated using Ti6Al4V specimens produced with a DMLS EOS system. The S/N data of Fig. 3 required the definition of an equivalent stress as discussed in [3]. This new method is being now intensively applied to different metallic alloys produced with different PBF systems and under different conditions. For example Fig. 4 demonstrates the directionality of the fatigue response (i.e. a cyclic stress parallel to the build direction affects most the material) of Inconel 718 produced with a Renishaw SLM system and subsequently heat treated. It is concluded that this technique is valuable for testing and qualifying the fatigue behavior of metal alloys obtained by the PBF technology.

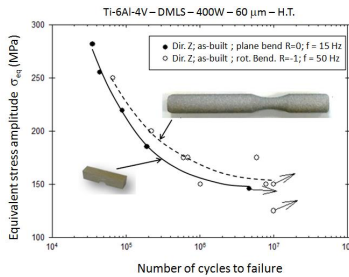


Fig. 3 Validation of new specimen geometry testing the fatigue response of DMLS Ti6Al4V

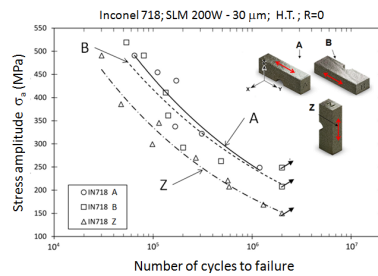


Fig. 4 Directional fatigue behavior of SLM Inconel 718

Additional observations and results related to the mechanical behavior of PBF metals obtained by various experimental mechanics techniques will be the content of the oral presentation.

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AM PROCESS SIMULATION

3D finite element analysis of molten pool behavior in selective laser melting process

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Key Words: *Selective laser melting, FE model, laser path simulator*

Laser-based additive manufacturing is a near-net shape manufacturing process able to produce net-shape 3D objects starting from metallic powders melted layer by layer. It permits to manufacture products that are very difficult to fabricate by the traditional processes, saving material and time. Despite the benefit, these manufacturing processes are very problematic to control because of the high number of involved parameters.

The numerical simulation can help to reduce the amount of experimental trial-and-error tests necessary to optimize the process, to minimize the time and cost of manufacture of the final product while maintaining its quality unmodified. The thermal behavior of the molten pool is one of the most critical factors that influence the laser deposition, as it affects geometrical accuracy, material properties and residual stresses. In this paper, a three-dimensional finite element model is developed to simulate the thermal behaviour of the molten pool. The analysis of laser powder bed fusion process is carried out using Ansys, a commercial finite element software.

The model is based on a discrete pulse laser scanning the material point by point. The material properties are temperature dependent and two different set of parameters are implemented for powder and solid.

The simulation makes it possible to analyse also the case of multi-path and multi-layer processes. The procedure involves a series of loop cycles that take into account the iterations on subsequent spots and layers. Due to cyclic behaviour the solution must be carried out at each iteration.

During the post process, the temperature of the elements is checked in order to evaluate which ones are over the melting temperature of the material. To track the time evolution of temperature data are stored at each solution step and then uploaded again. The elements are updated with a mapping procedure based on their number. Previous information becomes initial condition for the actual iteration [1,2]. The analysis allows also for the simulation of recoating process. The thermal behaviour of molten pool halved along the symmetry plane is illustrated in Fig. 1.

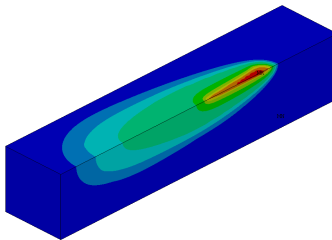


Figure 1 - Thermal behavior of molten pool.

A scanning strategy, including both a meander path and the contour, is simulated by an external software code. To track the coordinates of laser application points a path simulator is built using MatLab. The simulator imports a CAD file with the geometry. Then it slices the model and calculates the path layer by layer. Once having both the path and the geometry, the laser pulse coordinates are used by Ansys to impose the thermal load in the defined spots. To improve the performances of the simulation the two software interact each other to solve the analysis. At the beginning a calibration procedure is carried out to fit the numerical solution with the experimental data [3]. Then the tuned model is used to simulate the real process. The result of the interaction between the path simulator and the FE code is illustrated in Fig. 2.

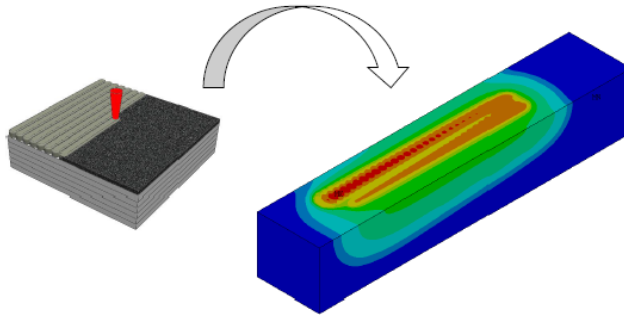


Figure 2 - From path simulator to FE analysis.

By this method, the temperature distribution and the geometrical feature of the molten pool under different process condition are investigated. Results from the FE analysis provide guidance for setting up the optimization of process parameters and develop a base for further residual stress analysis.

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A Smoothed Particle Hydrodynamics Model for Melt Pool Dynamics in Laser Beam Melting of Ni-based Alloy 718

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Key Words: *Additive Manufacturing, Laser Beam Melting (LBM), Smoothed Particle Hydrodynamics (SPH), Melt Pool, Simulation, Computational Fluid Dynamics (CFD)*

Laser Beam Melting (LBM) is an additive manufacturing process which simultaneously involves multiple physical phenomena such as thermo-fluid dynamics, irradiation and phase change. Therefore, an understanding of the significant underlying physical processes and their interaction is very challenging. This problem can be addressed by means of a numerical modeling approach. Within this work a numerical model of LBM based on the meshless computational method Smoothed Particle Hydrodynamics (SPH) is presented. SPH was originally introduced by [1, 7]. Due to its meshless nature and, especially, in multi-phase formulation suggested by [2, 3] it is very convenient for the simulation of additive manufacturing processes such as LBM.

Furthermore, its implementation turns to account the parallelization capabilities of GPGPUs for achieving a reduced computation time. Physical phenomena such as the heat transport due to laser beam radiation, thermal conduction, phase transitions, convection, and effects related to surface tension and thermocapillarity are considered. Approaches for modeling the recoil pressure induced by evaporation are applied - following essentially [6, 5, 4].

The buoyancy due to temperature gradients is taken into account by means of the Boussinesq approximation. The relevant material data for the investigated Ni-based alloy Inconel718® are implemented as a function of temperature and the required values are taken from literature [11, 9, 10, 8].

The simulation results are compared with experimental data of single melt tracks to evaluate the validity of the model with regard to the process parameters (e.g. scanning velocity, laser power).

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Numerical Analysis of the Fluidynamic Interaction between Carrier Gas and Powder

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Key Words: *Modelling, Euler-Lagrange Approach, Extended Discrete Element Method (XDEM)*

1 Introduction

Selective laser melting (SLM) or electron beam melting (EBM) avoid the constraints of classical subtractive manufacturing and thus, offer a large flexibility for product design. However, thermo-physical processes with complex interactions occur on different length scales and are still not known in detail. In particular, the flow of metallic powder interacting with a carrier shielding gas plays a crucial role during additive manufacturing and therefore, the objective of the current contribution is to analyse numerically the complex fluid-dynamic interaction between powder grains and a carrier gas under relevant geometry and flow conditions. For this purpose an Euler-Lagrange approach is applied that treats the powder by the Discrete-Element-Method (DEM) and describes the carrier gas flow by advanced Computational Fluid Dynamics (CFD) [3]. Hence, the resulting numerical concepts describes the trajectory of powder grains and successively the region of impact into the melt pool, with an acceptable computational burden.

2 Results

As mentioned above, advanced multi-physics simulation technology derived from the Extended Discrete Element Method (XDEM) [2, 1] was applied to predict the injection of metallic powder into a carrier gas atmosphere as shown in fig. 1.

The velocity distribution following a toroidal pattern forces the powder to a converging flow in the centre of the arrangement as depicted in fig. 1. Since powder grains have a negligible inertia, they follow closely the streamlines of the carrier gas. However, the proximity of the work piece forces the carrier gas flow into a diverging flow field that is torus-like as found for selective laser melting. Powder grains also adapt to the carrier gas flow configuration which let the powder grain diverge into four jets. Thus, the four jets impact the melt pool at distinct positions and do not have a single focal point for deposition of the powder.

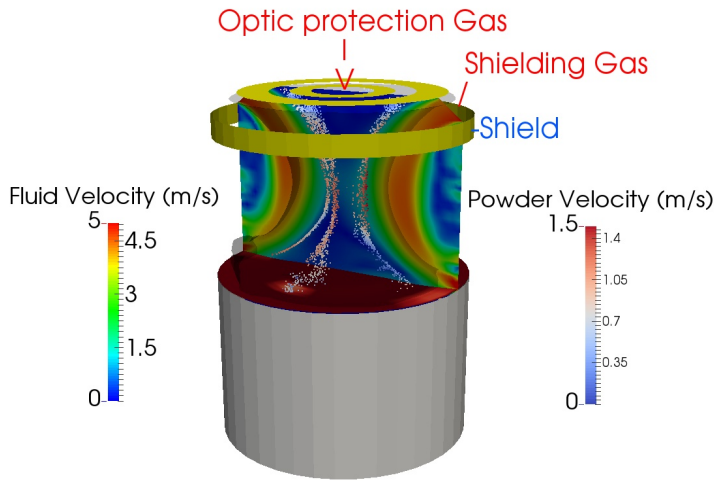


Figure 1: Centre cut through the velocity field with metallic powder impacting the melt pool

3 Summary

An advanced multi-physics simulation technology based on the Extended Discrete Element Method (XDEM) was employed to predict both the fluid dynamics of a carrier gas and the trajectory of metallic powder. Carrier gas flow is described by Computational Fluid Dynamics (CFD) to predict both velocity and pressure fields, while the trajectories of the metallic powder grains were obtained through the Discrete Element Method (DEM). This technology allowed tracking the grains and their impact positions on the work piece. Hence, numerical techniques are complementary to experimental work and lead to a deeper understanding of the underlying physics.

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Dynamic methods of nanoparticle assembly: high-velocity impact and shock-wave compaction

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Key Words: *Nanoparticle Assembly, High-Velocity Impact, Shock-Wave Compaction, Molecular Dynamic Simulation*

In the frames of additive manufacturing, assembly of metal particles into an object is traditionally performed by sintering or melting under the action of laser irradiation [1-3]. Here we consider another approach to the assembly, which is connected with attachment of nanoparticle by means of severe plastic deformation induced by a high-speed collision or a shock wave action. This deformation improves the contacts, increases the contact areas and allows the particles to be attached by interatomic forces. We refer the considered methods as dynamic methods of nanoparticle assembly and investigate here the corresponding elementary processes by means of molecular dynamics (MD).

Normal collision of single Cu nanoparticle with Al surface, resulting plastic deformation and adhesion have been previously investigated by part of us [4]. Now we investigate inclined collision, interaction with surface roughness (see Fig. 1) and multiple collisions. LAMMPS [5] is used for MD simulations and OVITO [6] is used for visualization and analysis. The inclined collision leads to decrease in the part of kinetic energy, which is spent on mutual plastic deformation of the nanoparticle and substrate. As a result, adhesion and imperfection decrease simultaneously together with the increase in the incidence angle. Interaction with surface roughness (Fig. 1) leads to more pronounced surface deformation, but decreases the generated dislocation length inside the substrate. Multiple collisions form porous structure with strong bonds between particles. Adhesion, nanohardness of the formed layers, as well as acceptable range of collision parameters are analyzed.

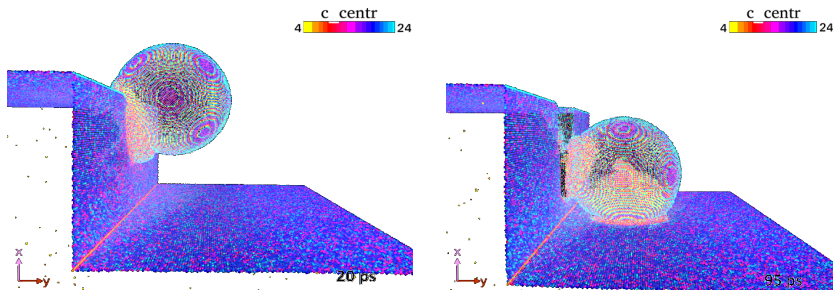


Figure 1. Collision of Cu nanoparticle $d = 16$ nm in diameter with a step-like protrusion on Al surface: the height of protrusion is equal to d , the overlap is equal to $d/4$; collision velocity is 500 m/s. MD simulations with about 10 million atoms: two time moments are shown.

Our previous MD investigations [7] have shown that entering of a shock wave on a free surface with nanorelief provokes a severe plastic deformation of the nanorelief elements. Here we analyze prospects of using this effect for consolidation of nanoparticles into solid layer (see Figure 2). Initial layer of nanoparticles can be deposited by the previously considered high-speed collision or, alternatively, by any soft deposition method. MD simulation show that shock compression pulses with nanosecond duration and amplitude about 10 GPa can be an efficient tool for nanoparticle compaction. Using of multiple pulses allows one to compact a layer of arbitrary thickness. Such compression pulses can be initiated by picosecond pulses of laser irradiation of the opposite surface or plate impact with an impactor of nanometer thickness.

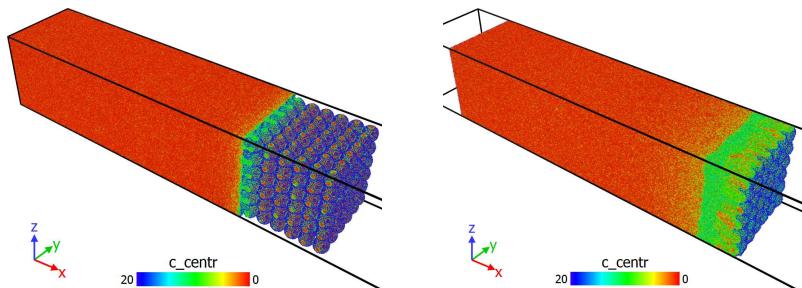


Figure 2. Shock-wave compaction of aluminum nanoparticles on aluminum substrate. Substrate thickness is 85 nm; nanoparticle diameter is 6 nm. Plane shock wave is induced by a high-velocity impact of a plate impactor with thickness of 40 nm and velocity of 800 m/s on opposite surface. MD simulations with 13.3 million atoms: initial (left picture) and final (right picture) states.

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3D Multilayer Grain Structure Simulation for Beam-Based Additive Manufacturing

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Key Words: *Additive Manufacturing, Numerical Simulation, Grain Structure, 3D, Multilayer, Cellular Automata*

The correlation of build parameters for beam-based additive manufacturing like scanning speed, beam power or hatching strategy on the resulting microstructure are still not fully understood. One of the key challenges lies in the difficulty to make in-situ observations during the build process. Technologies operating under vacuum conditions, like Selective Electron Beam Melting (SEBM), severe these challenges. Especially the high temperatures and long build times prevent the direct investigation of the resulting microstructure. Numerical modeling and simulation allows not only the direct observation of the influence of various build parameters. Constantly increasing computational power enables the calculation of a multitude of parameter combinations simultaneously and thus the virtual optimization of the build process without the need of time- and cost-intensive experiments.

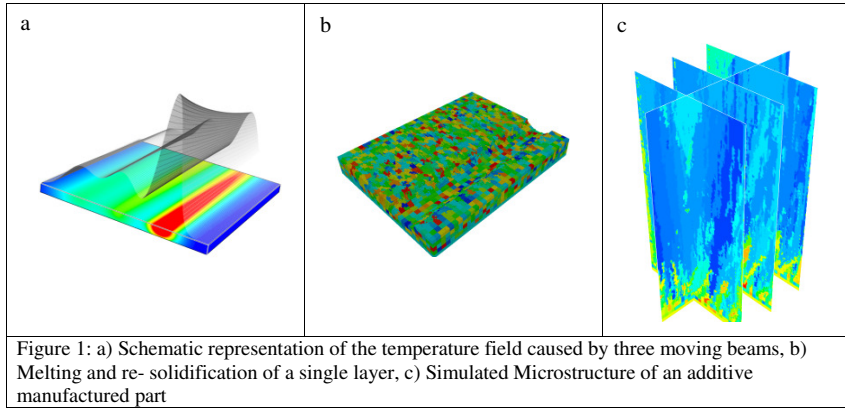
The last few years have brought substantial progress in the development of numerical models, especially in 2D Simulations [1-2]. These sophisticated models are capable – among others – to predict the resulting microstructure caused by distinct build- and material parameters. Modeling the grain structure in 2D is limited, e.g., grains developing and growing outside of the calculation plane are not considered. Thus, it is not possible to take the common phenomenon of piercing grains that cut through the observation plane into account. Furthermore, the variation of the melt pool geometry due to various hatching strategies is disregarded with these models.

To consider those phenomena, it is necessary to model the build domain in 3D. The 3D grain growth model presented here bases on a cellular automata model [3]. This algorithm was originally developed for growing of dendrites into an undercooled melt, so various adaptations for additive manufacturing had to be made which will be demonstrated in this work. The beam is modeled as moving heat source using an analytical temperature solution [4] (cf. Figure 1a). This analytical solution is well suited for the use of our grain growth model as comparisons of the melt pool shape and dynamics with experimentally observed characteristics [5] show.

The very fine spatial and temporal resolution necessary for grain growth simulation cause an enormous challenge to the computational hardware as well as the applied algorithms. Therefore, our algorithm is massively parallelized and runs on an HPC-Cluster containing thousands of computation cores. With this computational power, it is possible to calculate a complete layer within minutes. This enables us to study the impact of various hatching strategies on the resulting microstructure of a complete additive manufactured part within reasonable time.

The presented numerical 3D grain growth model enables us to investigate the effects of various build parameters and hatching strategies on the resulting microstructure. It is not only capable of simulating the melting and re- solidification of a single layer (cf. Figure 1b). Multiple successive runs with

individual beam guiding parameters enable the investigation of the effect of various hatching strategies on the 3D microstructure of an additive manufactured part (cf. Figure 1c).



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Numerical Modeling of Microstructure Evolution During Directed Energy Deposition Additive Manufacturing of Ti-6Al-4V

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Key Words: *Directed Energy Deposition, Ti-6Al-4V, Microstructure, Modeling*

The Directed Energy Deposition (DED) process is a metal additive manufacturing (AM) process in which localized moving heat sources having high-intensity are used to melt and fuse powder materials. The complex and non-uniform thermal gradients generated by rapid heating and cooling cycles in DED process directly affects the microstructural characteristic and thereby the ultimate mechanical properties of AM fabricated parts [1,2]. Hence, understanding how the AM process affects the part microstructure is of critical importance. The objective of this paper is to present a three-dimensional Finite Element (FE) based thermo-kinetics model to investigate microstructural evaluation during the Laser Engineering Net Shaping (LENS) process [3], which is one of the representative processes of DED. The proposed model couples the FE heat transfer calculations [4] with phase transformation kinetics and microstructure of Ti-6Al-4V. The microstructural model based on Kelly's [5] and Charles's [6] models, which enables calculation of the Widmanstätten colony and basketweave phase fractions, and alpha lath width [7] during heating and cooling cycles.

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Quantitative cellular automaton model for the simulation of anomalous eutectic growth during SLM process

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Key Words: *Cellular Automaton Solidification, Eutectic Growth, SLM*

Anomalous eutectic is formed during solidification of binary eutectic alloy. Anomalous eutectic was firstly observed during the undercooled solidification of Ag-Cu[6] and Ni-Sn[3]. Three insights of anomalous eutectic growth mechanism have been summarized[4]: one phase is continuous and the other is discontinuous[1], both phases are continuous[3], both phases are discontinuous[2, 7]. Anomalous eutectic morphologies were also found at the bottom of melt pool during SLM of Ni-Sn eutectic powders once and twice[5]. Up to date, the morphological evolution of anomalous growth is still unknown, such as that how is the β -Ni₃Sn matrix formed and what is the transition mechanism from anomalous eutectic to lamellar eutectic. We focused on the microstructure evolution of anomalous growth during laser remelting of Ni-Sn alloy powders. Fig.1 shows the backscattered electron images of anomalous eutectic at the bottom of melt pool after laser remelting Ni-30wt.%Sn powders twice. The details of experiments can be seen in author Lin's recent paper[5].

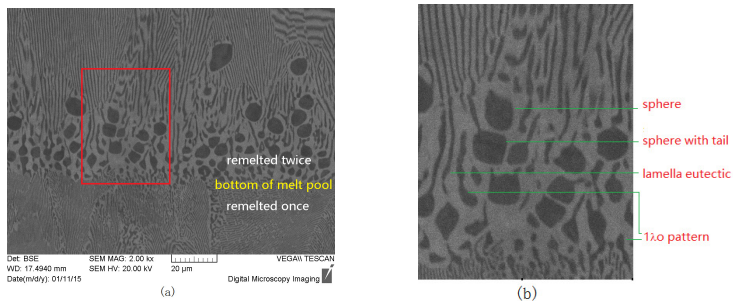


Figure 1: Backscattered electron images of anomalous eutectic at the bottom of melt pool after laser remelting Ni-30wt.%Sn powders twice

Quantitative cellular automaton (CA) model for anomalous eutectic growth is introduced. It is indicated that anomalous eutectic growth is not simply caused by rapid solidification. A “remelting→slowly

solidifying→rapidly solidifying” process is essential. Anomalous eutectic is formed in the “slowly solidifying” region. CA simulation of microstructure evolution shows that larger sphere α -Ni nucleations are rapidly wrapped by β -Ni₃Sn; smaller α -Ni nucleations grow into lamellar eutectic coupled with β -Ni₃Sn. Thus the competitive growth between anomalous and regular eutectic has been observed. We also discover that the cooling rate determines whether it is epitaxial growth of regular eutectic or anomalous eutectic growth with α -Ni nucleations.

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Laser command generation for direct energy deposition with time-domain thermal conductivity simulation analysis

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Key Words: *Direct Energy Deposition, Thermal Conductivity, Laser*

Direct energy deposition (DED) is an additive manufacturing (AM) process where focused thermal energy is used to fuse materials by melting as they are being deposited as shown in Fig. 1. DED attracts much attention from aerospace and automobile industries because of its applicability to complex shape production with high efficiency. In terms of laser AM technologies for metals, many researchers evaluate mechanical properties of the produced parts. For example, the strength of the components manufactured in DED is often analyzed in terms of density, and several researchers take experimental approaches to reduce the void inside them [1]. The relation between the microstructure and its mechanical characteristics is also investigated for superalloys, such as Inconel 625 [2] and Ti-6Al-4V [3]. Most of these studies indicate the necessity of laser power modification in metal AM process to enhance the specific strength and obtain a proper metal structure.

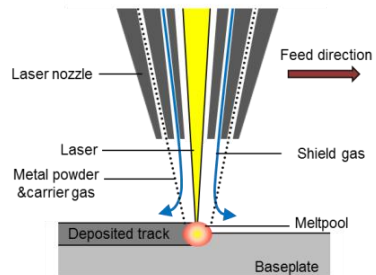


Fig. 1 Schematic of direct energy deposition (DED) process.

On the other hand, shape accuracy is also an important factor in the manufacturing industry in terms of reliability. Although DED provides high production efficiency comparing powder bed fusion (PBF), it is difficult to enhance shape accuracy in DED. A simulation can ensure shape accuracy by predicting the produced shape from the production conditions; thus, an accurate time-domain simulation is proposed for PBF [4]. However, in case of DED, the dynamic movement of metal powder and large heat supply render process analysis difficult.

Considering the shape of deposited part strongly depends on the melt pool size in DED, the melt pool temperature should be kept constant and overheating must be avoided. From this viewpoint, a laser command optimization is proposed in this paper to maintain the melt pool temperature in DED based on a thermal conductivity simulation. A laser power command is a pre-requisite for the proposed method. Therefore, the deformation due to overheating can be avoided only with a feedforward

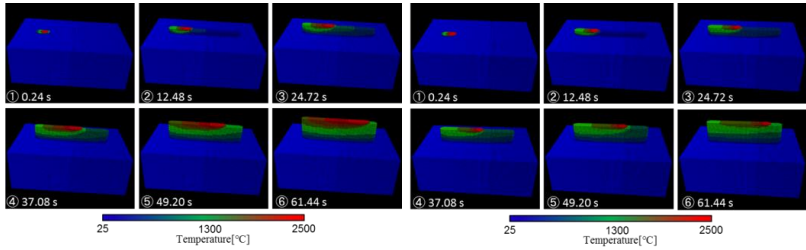


Fig. 2 Temperature distribution simulation result for DED using a constant laser power.

Fig. 3 Temperature distribution simulation result for DED using laser power modified with gradient descent.

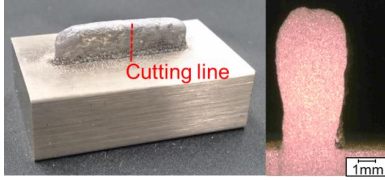


Fig. 4 Deposited object produced on a single track under constant laser power of 2000W.

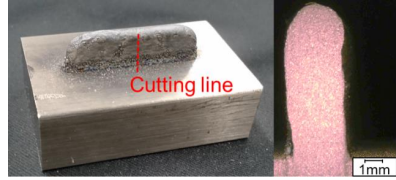


Fig. 5 Deposited object produced on a single track under the calculated laser command.

control. The calculated laser power command is installed to the DED machine and investigated by depositing a wall-shape part with Inconel625 and evaluating shape accuracy.

Applying a finite-difference method with a voxel model, heat distribution in DED can be approximately predicted. The proposed method calculates the optimal laser power command to avoid overheating in DED by introducing gradient descent to the moltpool temperature in the simulation. The moltpool temperature gets higher in higher layers under constant laser power in the simulation (Fig. 2), on the other hand, overheating is certainly avoided with the proposed laser power command as shown in Fig. 3. By introducing the calculated laser command to wall-shape deposition, the proposed method is evaluated from the viewpoint of shape accuracy. Although the width of wall gets larger in higher layers due to overheating under constant laser power (Fig. 4), the deformation due to overheating is suppressed under the calculated laser command with the proposed method as shown in Fig. 5.

Not only single track deposition but also corner track and circular track are evaluated in this study, and the experimental results clearly shows that the proposed method certainly improves shape accuracy of deposited parts in all these tracks.

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The Effects of Loose Powder on the Results of the Temperature and Distortion Simulation for Laser Powder Bed Fusion

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Key Words: *Additive manufacturing, finite element analysis, simulation, Laser Powder Bed Fusion, loose powder, residual stress*

The warping of parts during Laser Powder Bed Fusion deposition presents a significant challenge to the process becoming an economically feasible method of component production. Component warpage frequently leads to part failure, resulting in expensive experimental trial-and-error iterations. This study shows that finite element modeling performed using Autodesk® Netfabb Simulation® can be used to quickly and accurately predict the distortion of part-level components and to indicate likely failure modes, thus circumventing costly failed builds. The simulation methodology will be described and extended to cases requiring the simulation of the full build plate, including the un-melted powder and multiple parts. It will be shown that the inclusion of the unmelted powder in the simulation leads to a significantly more accurate temperature distribution prediction (Figures 1 – 2). The effect of part interaction and placement location on the build plate will be demonstrated for both the thermal and mechanical response. Model predictions will be compared to experimental distortion measurements.

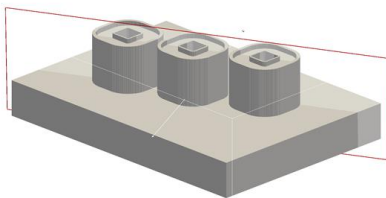


Figure 1. CAD model of the AM parts on the build plate

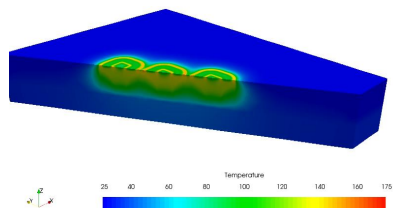


Figure 2. Simulated temperature distribution in powder bed (including the temperature in loose powder)

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Experimental validation of a numerical thermal numerical model of EBM process for Ti6Al4V

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Key Words: *Electron Beam Melting (EBM), experiment validation, multi beam*

The Electron Beam Melting process (EBM), or also known as Electron Beam Additive Manufacturing (EBAM), is an additive manufacturing (AM) process that use an electron beam to melt metallic powders. Although the use of an electron beam in the AM field is relatively recent, several applications have already been made in the aerospace and medical fields [1, 2]. To increase the applicability of the EBM process and to make it more reliable different modelling techniques will be helpful tools. Modelling may have the potential to reduce the optimisation time when compared with experimental trial and error approach. In fact, by means of numerical modelling, process stability could be reached by exploring virtually what-if scenarios. However, experimental validation is necessary to ensure the accuracy of the modelling. The aim of this paper is to validate the effectiveness and reliability of the Finite Element (FE) thermal model developed in a previous work [3] by comparing numerical results and experimental measurements.

Two different scanning strategies were studied: multi beam and continuous line melting. In multi beam melting, separate short melt lines (multi beam lines) are activated at different points along the predefined melt track. The electron beam jumps sequential between the short lines until the complete melt track is finished. Continuous line melting means that the complete predefined melt track is melted from the start point to the stop point in one single sequence. The following parameters were investigated: beam speed, beam size and length of multi beam lines. A novel experimental setup was used in which several single line melt tracks were manufactured in an Arcam Q10 system. Standard Arcam Ti6Al4V powder was used and the layer thickness was set to 0.05 mm. Microscope images were used to acquire the width of the melt pool at different positions along the melt tracks. The experiments were replicated by numerical simulations using the model in [3] and the Abaqus software. A good agreement between simulations and experimental data was found. Further improvements of the existing model and the possibilities to investigate multiple lines melting (hatching) are discussed.

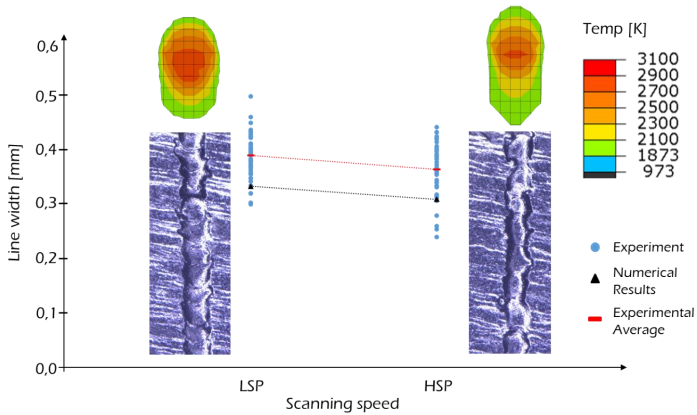


Figure 1-Single line multi beam melting. Comparison between numerical and experimental results for two different values of scanning speed.

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Predictive Numerical Simulations of Processing Windows for Powder Bed Based Additive Manufacturing

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Key Words: *Selective Electron Beam Melting, Processing Window, Ti-6Al-4V*

Additive manufacturing processes inhere the opportunity to tailor the properties of parts for specific requirements. These properties are strongly connected with the porosity, local composition and microstructure of the parts. Effects such as channel-like cavities with heights up to several millimeters, changes in the composition due to evaporation or anisotropic properties due to a textured microstructure may arise. These phenomena observed in experiments are combined into a processing window. Our simulation tool has the predictive capability to reproduce these effects. The results show the unique power of simulating macroscopic millimeter sized domains with a mesoscopic approach [2, 3]. This approach is capable of resolving the stochastic powder bed, the hydrodynamics of the melt pool and the microstructure evolution. Regular porosity, the stochastics of channel-like porosity, composition changes and grain structure evolution can be revealed simultaneously, which is not accessible with macroscopic setups.

The main objective of this work is to show the influence of stochastics on the final samples that trigger e.g. the evolution of channel-like cavities (as described by Bauereiß et al. [1]). The numerical investigation reflect the primary experimental results of sample processing windows of selective electron beam melted Ti-6Al-4V. This demonstrates the predictive capability of our simulation tool and simplifies the determination of suitable processing windows.

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Reduction of local overheating in selective laser melting

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Key Words: *Selective Laser Melting, Finite Element Method, Recoating Blade Collision*

The problems associated with local overheating during Selective Laser Melting (SLM) were often observed recently [1, 2]. If local overheating occurs, large molten zones above the building surface can arise. Such molten zones collide with the recoating blade and as consequence cause its damage and/or process break-off. An example of local overheating is shown in Figure 1. The geometry from Figure 1 is manufactured from a nickel-based superalloy with a standard additive manufacturing (AM) process. In our process the AM layers have 20 μm thickness. To avoid process interruption due to overheating we use flexible silicone rubber lip instead of hard recoating blade. Figure 1 demonstrates that the heat from the corners of the considered geometry cannot be transported appropriately. Therefore these corners are about 360 μm higher than the rest of the top surface. Such high molten zones not only cause blade crashes, but they are also unacceptable for quality control.

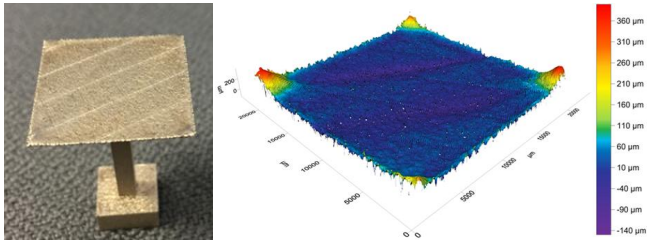


Figure 1: SLM geometry build with a standard process and its top surface profilometry

To identify critical areas in the AM process we simulate melt pools for representative volume elements (RVEs) shown in Figure 2. The slope angle α of RVEs is chosen identical to the slope of the geometry from Figure 1. RVEs with various lengths l are simulated in order to illustrate the different blocked paths of the laser beam. For an overheated area as in Figure 2(b), the melt pool spreads over multiple tracks, so that a large molten zone is formed. From the simulated width of this zone an estimation of the corresponding elevation of the top surface can be done. Figure 2(c) shows, that in outside the overheating area, the melt pool size follows the expectation.

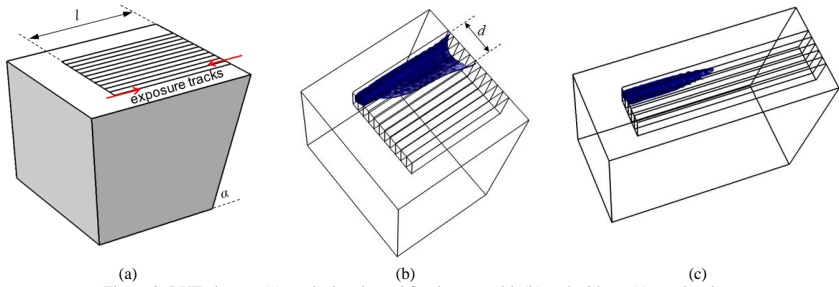


Figure 2: RVE element (a), typical melt pool for the area with (b) and without (c) overheating

Attempts to simulate melt pool size and update AM process parameters in order to reduce overheating were previously made, e.g., in [3]. The authors raise the velocity of laser beam layerwise depending on the slope angle. In opposite to [3], we identify critical areas by sample RVE simulations and reduce power input only in these areas. We tested the identification of critical regions for overheating on the geometry illustrated in Figure 1. We identified the size of the area around corners where the process parameters should be changed. We manufactured the inner volume of the reference geometry with the same AM parameters as above and reduced the power input in the corners. Figure 3 shows the result of this strategy. From Figure 3 it is clear that with our strategy we significantly reduced the overheated areas.

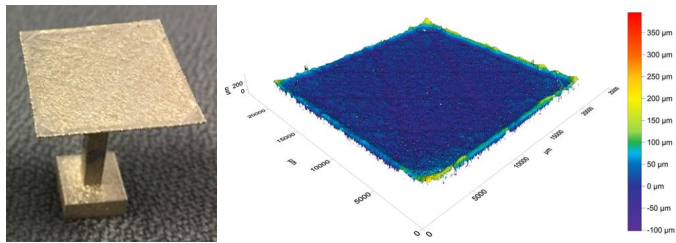


Figure 3: Reference geometry build with reduced power level in the corners and corresponding profilometry

In summary, we developed a method for systematic simulation of local overheating. It identifies critical areas that might cause AM process crashes. The method was successfully demonstrated on the reference geometry.

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A Comprehensive ICME Toolset for Additive Manufacturing

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Starting in 2009, we set out to build a comprehensive integrated computational materials engineering (ICME) toolset for additive manufacturing. Our goals included the ability to predict meltpool-scale phenomena for full-scale components faster than the part could be built. To date we have completed and deployed in commercially available products a Mechanics Solver which computes layer-by-layer strain accumulation for the purposes of residual stress, distortion and related predictions, and a Thermal Solver capable of predicting thermal history, phase transitions, meltpool characteristics and porosity at 10-30 micron resolution for full-scale components. We are currently working on transitioning our Cellular Automata tools for microstructure predictions and our Dislocation Density based Crystal Plasticity tools for part performance predictions from research code to production code for commercial release over the next 24 months. An overview of these tools, their capabilities, and validation activities will be included in this talk.

Simulation of LMD repairs with a theoretically non-weldable nickel-based superalloy

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Key Words: *Additive manufacturing, Superalloy, Residual stresses*

As a well-known nickel-based superalloy, Inconel 738 LC (IN738LC) is currently used in the hot sections of aircraft engines. However, IN738LC exhibits a high propensity to hot cracking during rapid thermal processing such as in foundry or in repairing operations. Therefore, a thermo-mechanical modelling of the laser metal deposition (LMD) process is developed here to compute the residual stresses built-up for this IN738LC. Simulations and experiments are performed to optimize the process parameters and to reduce the cracking sensitivity by finding a cracking criterion which could be related to the laser-induced metallurgical phenomena.

IN738LC exhibits enhanced mechanical properties through the precipitation of an ordered phase called γ' , made of $\text{Ni}_3(\text{Al,Ti})$ in the γ austenitic matrix. The downside of such a precipitation is to lower the weldability of the material because of HAZ cracking [1]. In the present work, a thermo-mechanical-metallurgical simulation of the process is developed using Z-set FEA software in order to have a better understanding of the repairing process. The model was used on several LMD repairs including different geometries as well as different operating conditions.

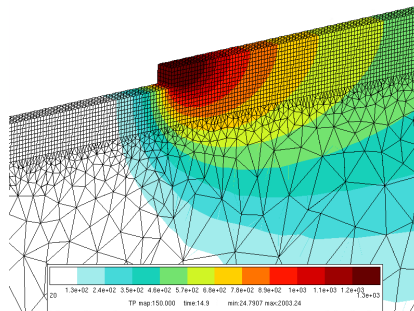


Figure 1: Thermal modelling of successive metal deposits

As the thermal modelling lies on the resolution of the heat equation, an analytical heat source is used consistently with the measured experimental power distribution. Heat exchanges are modelled through convection and radiation losses.

Experimental tests and simulation are compared using the size of the melt pools as well as temperature fields provided by K thermocouples. The successive metal deposits are taken into account using the quiet element method which consists in premeshing all the elements and adding them to the thermal modelling as soon as they are irradiated by the laser source [2]. The volume of activated elements depends on the dimensions of experimental deposits.

A weak coupling is actually used, thus meaning that the thermal modelling results are used as data entries to compute the residual stresses and γ' volume fraction.

Inactivated elements are given a low stiffness value in order to neglect their contribution in the numerical process. The thermo-mechanical simulation reveals high tensile residual stresses near and in the metal deposit. These high tensile residual stresses are therefore counterbalanced by moderate residual compressive stresses further away from the deposit [3].

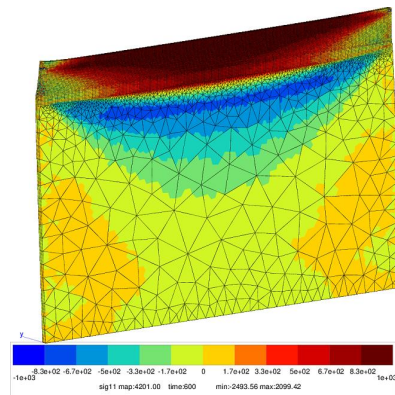


Figure 2: Longitudinal residual stresses

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Adaptive domain reduction for simulation of the additive manufacturing process

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Key Words: *Thermo-structural simulation, domain reduction*

Common additive manufacturing technologies for metals involve a focused energy beam, with either laser or electron beam, to heat and melt powder material, which then cools down and solidifies. As the object is being manufactured, the higher energy heat source introduces thermal distortion and residual stress. While additive manufacturing is a promising manufacturing method, for its capability to extend the design space offered by traditional manufacturing, at the same time, the process is inherently complex. The geometry and mechanical performance of the printed object is highly influenced by the raw material and by the process parameters, and could make the final product deviate from the original design and expected performance. Modeling and simulation of the additive manufacturing process can be used to test different parameters configurations in a cheaper way and to perform non-invasive virtual validation of the part quality.

We developed an approach to perform thermo-mechanical simulation of the additive manufacturing process, with particular focus on selective laser sintering and direct energy deposition process type, at a macroscale level, that integrates with Siemens NX software, as an add-on, to automatically retrieve design and manufacturing process parameters, such as the toolpath, that are then used as input for the multi-physics simulation. The simulation components of the workflow also leverage NX capabilities, specifically NX Nastran solvers for both thermal propagation and for structural behavior. These two problems are weakly coupled in the work flow. One characteristics of the developed approach is that the computational domain is continuously extended to account for the deposition of new raw material, by addition of new elements, to follow the toolpath in the part generation process. This time-varying computational domain has introduced additional complexity to the model. More importantly, computational cost of each thermo-structural run increases during the course of the simulation, as more material is being added to the computational domain. To reduce the computational burden, a domain reduction method was introduced, based on the observation that, as the printing process proceeds, the solid material composing the first deposited layers of the part being printed has already cooled down or has very little variations over time, hence showing negligible structural deformation and influence on the temperature of the upper layers. Hence removing those layers in simulation of subsequent layer will reduce the computational cost, especially for large parts, without dramatically reducing the fidelity of the results. The full part result can always be recovered using the latest information computed for each layer, for visualization or for further processing.

The steps of the proposed algorithm for the adaptive simulation reduction are the following. Every time a new layer starts to be printed, perform:

1. Layers selection: Select the number of layers (N_L) below the current layer (L_C), to be retained in the next simulations, either a priori (based on past knowledge) or in an adaptive way.
2. Boundary conditions modification: Modify the boundary conditions at the interface between the retained and the omitted portions of the part, for both the structural and the thermal simulations to be performed next.
3. Simulation of selected layers: Perform the coupled thermal and structural simulations of the current layer and the top N_L layers below it.

The boundary conditions to be prescribed at the interface between the retained and the omitted portions of the part are selected as follows: for the thermal simulation, a modified convection boundary conditions can be prescribed to simulate, in a lumped parameter fashion, to approximate the presence of the omitted printed layers. If we define h the actual convection coefficient from the outer surface of the object to the ambient, k the conduction coefficient of the solid and S the thickness of one layer, the lumped heat transfer coefficient (\hat{h}) to use is defined as:

$$\hat{h} = \frac{h * k}{k + h * (S * (L_C - N_L))}$$

For the structural simulation, the interface between the retained and the omitted portions of the part is constrained to move only in a plane parallel to the building plane.

Preliminary results show that this algorithm provides good agreement between the full domain simulation and the reduced one, in terms of temperature while reducing the computational time. An example is shown in Figure 1. In this case, 7 layers were retained for the simulation and, approximately 25% of the simulation time was saved. On the reported screenshot, there is a good general agreement in the temperature field of the simulated layers between the full domain and reduced domain simulations. The error on the maximum temperature value is only 1.3%.

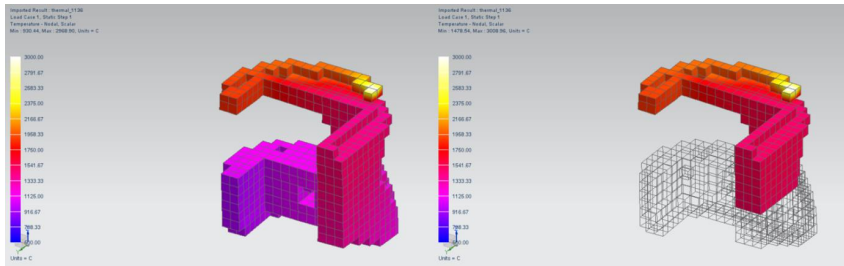


Figure 1 - Comparison between full domain simulation (left) and reduced domain simulation (right) with $N_L=7$, for a given time point. The variable compared is temperature.

Thermo-mechanical simulation of selective laser melting at layer scale

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Key Words: *Selective Laser Melting (SLM), Layer scale, in-process strain measurement*

The aerospace industry is interested by selective laser melting, a powder layer based additive manufacturing process that offers great perspectives of weight minimization. However, stress relaxation, or even cracking, can occur during the process. It is therefore essential to simulate this process to minimize stress, strains and guarantee a good quality of the finished parts.

Some models focus on the laser/material interaction and the physical phenomenon that occur locally on the melt pool, such as fluid flow or Marangoni movements [1]. This type of study is useful, since it defines local boundary conditions, but the required computations times make them unable to be used for industrial production. Some attempts has been made to adapt to the SLM process a less precise model initially developed for the simulation of Laser Metal Deposition (LMD) but the calculus are still extensively time consuming [2]. Therefore, some studies simulate this process using a larger scale using an equivalent thermal loading which is constant for each layer [3]. However, the effect of the laser path cannot be taken into account and non-symmetrical deformations cannot be predicted with such assumptions.

In order to get a quick but yet pragmatic estimation of the deformations, a weakly coupled thermo-mechanical model has been developed. The temperature is first computed before being used as an input data of the mechanical model which predicts the formation of stresses and deformations.

The part and the base plate are both meshed using Zébulon/Zset before the calculation. In order to save calculation time, the air and the powder bed are not meshed. The effect of the powder bed is taken into account by using different convection and radiation coefficients for the solid/powder interface and the solid/air interface. For each layer, the mesh representing the part is cut to the actual height and is coarsened in the lower layers where the thermal gradients are less important. The thermal model is based on an equilibrium equation between the heat flux representing the effect of the laser and the heat losses due to conduction, radiation and convection. The main interest of the present work is the use of an equivalent heat source which is defined on a 2D surface with a function of time and space ($q = f(x,y,t)$). An equivalent mobile heat flux can then be describe to represent, not the precise laser path, but the global travel of the heat flux over the building surface (Figure 1). For each layer, the thermal field described on this 2D mesh is then applied on the top surface of the 3D mesh representing the corresponding layer of construction.

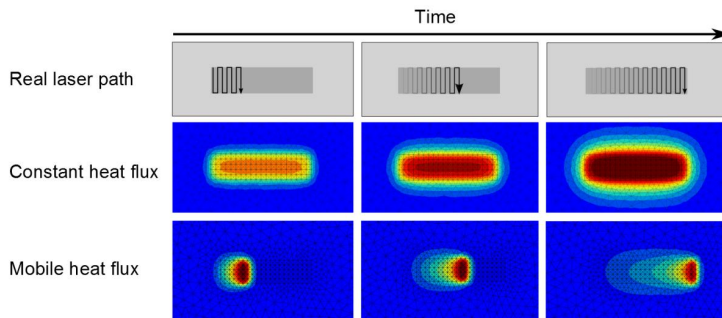


Figure 1 - difference between the real laser path, a constant heat flux and a mobile heat flux

Stress measurement methods are destructive and cannot be used in the additive manufacturing machine during the process. The model has been compared to experimental measurements of the in-process base plate deformations using a method developed by Van Belle [3]. A specimen is built on a 2mm thin base plate (Figure 2.a). As the stress and strains are induced by the thermal history, it is important to measure the temperature during the process and to correlate it with simulation. Because of the presence of powder around the part, it is not possible to measure the temperature in-situ with an optical system as a thermal camera. Thermocouples have been welded under the plate in order to be close to the melt pool during the first layers. During the process, the base plate is deformed by the stresses induced by the repeated thermal cycles. These deformations are measured by strain gauges located under the base plate as the thermocouples (Figure 2.b).

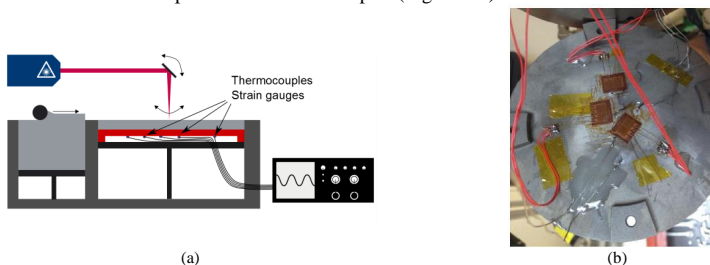


Figure 2 – (a) Experimental setup and (b) Strain gauges and thermocouples located under the base plate

The model shows good correlations with the experiments, both thermally and mechanically. A sensitivity study showed that model and experimental results suits the best when the external temperature around the part is artificially and progressively increased during the process. Further experiments and simulations will be performed in order to identify if this is related to the influence of the elevation of temperature in the powder layer during the process.

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Reduced Order Model for Selective Laser Melting Processes using the Finite Cell Method

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Key Words: *Finite Cell Method, Multi-level hp adaptivity, Reduced Order Model, Proper Orthogonal Decomposition, Discrete Empirical Interpolation Method, Selective Laser Melting*

A reduced order model (ROM) was used in conjunction with the finite cell method (FCM) [3] and the multi-level *hp* version of the finite element method [4] in order to simulate temperature distribution in selective laser melting (SLM) processes. It has been observed in [1] that for nonlinear problems, standard ROM does not lead to a significative speed up of the computational time. In fact, the method allows to reduce the number of degrees of freedom of the linear system to be solved, but it still requires to assemble the complete system of equations on the full order model (FOM). Therefore, in problems involving nonlinearities, the linearized system has to be recomputed at each iteration of the Newton-Raphson scheme. In [2] a specifically designed interpolation method, the so called discrete empirical interpolation method (DEIM), is introduced. DEIM allows to extend classical ROM computations and make them suitable to treat nonlinear problems. In this work a POD-DEIM algorithm is used together with FCM within an SLM parameter-optimization framework. It is shown that the combination of the methods mentioned above can lead to a considerable speed-up factor as compared to the non-linear FOM. First studies show that the resulting reduced order model is able to generate accurate results not only for the specific parameter-set for which it was designed for but also for variations. This opens the path to using the developed ROM for parameter-optimization of the production process.

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A reduced order modeling approach for fast thermo-mechanics simulation of additive layer manufacturing

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Key Words: *Reduced Order Modeling, Additive Manufacturing, Simulation, Thermo-mechanics*

The adoption of Additive Manufacturing (AM) technologies at the industrial level has set out several challenges for the scientific community, ranging from the study of the interactions at the scale of the particle to the prediction of the mechanical state of the final part [1, 2]. This work is only concerned with the thermo-mechanics simulation for predicting residual stresses and distortions of the part. AM has brought several challenges to this field, among which we highlight the following:

- The geometric complexity. The flexibility of AM technologies allows for the use of topology optimization in the conception stage. This results typically in thin parts, very sensitive to distortions. Complex geometries also require finer meshes and hence, large numerical models.
- The strong dependence on the fabrication strategy. This is mainly due to the non-linear modeling required in order to account for the complex physics transformations.
- The incremental nature of the process. To build a single part, hundreds of layers have to be deposited, each one being made of a succession of hatches which are less than 1 mm thick. How part-increments should be tracked by the simulation is an open question that requires a compromise between accuracy and computational cost.

These difficulties explain why standard approaches (e.g. finite elements combined with the so-called *born-dead-elements* technique [3]) perform quite disappointingly, yielding prohibitive execution times. Substantial effort is being made in order to devise new computational strategies. Among them, we can highlight mesh adaptivity approaches [4], which are based on a sequential refining/coarsening strategy near to the location of the spot. These approaches are still quite expensive, and moreover, mesh coarsening has implications on both the accuracy and the fidelity of the geometry description. However, it should be noted that current limitations in AM simulation for predicting residual stresses and distortions come mainly from the computational expense entailed by the numerical model, rather than from

the complexity of the physics modeling. Therefore, reduced order modeling (ROM) methods [5] seem to be good candidates for alleviating the computational cost. In this work, we propose a ROM approach which is founded on two basic hypothesis:

- A two-zones substructuring. There exist a region near to the spot (say the last few deposited layers) in which complex physics transformations take place. We call this zone the *process* region. Outside the process region, the material is assumed to be somehow stabilized, i.e. plastic deformations do not evolve anymore, or if they do, it is only due to large-displacement effects. We call this zone the *structure* region. The relative extent of both regions will be analyzed in this work.
- A two-stages simulation strategy. We postulate that, in most of cases, plastic strains created *locally* in the process region are nearly insensitive to whether the *global* equilibrium equations are solved in a small-displacement or in a large-displacement framework. We shall provide numerical evidence of the validity of this hypothesis for several parts of industrial interest.

In view of these hypothesis, we propose a two-stages-and-two-zones computational strategy. In the first stage, a thermo-mechanical simulation would be conducted within a small-strains framework. Then, in the second stage, we propose to solve a large-displacement equilibrium problem, defined only in the final geometry, which accounts for the plastic strains created in the first stage. Note that new plastic strains may be created due to large displacements, especially when dealing with thin geometries. Now, applying the two-zones substructuring hypothesis in the first simulation stage, we have that plastic strains are created exclusively within the process region. This implies that the structure region can be assumed to behave in small-strains elasticity during the first simulation stage, provided that we account for the cumulated plastic strains. This opens the door for reducing the complexity of the structure region, thanks to the relatively simple behavior of this part. The complexity reduction can in principle be achieved in several manners. In this work, we shall discuss a substructuring approach based on reduced order modeling techniques. The complexity of the structure region is greatly reduced, and as a consequence, it is possible to conduct the first simulation stage at a cost which depends roughly on the size of the process region.

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Modelling of Stresses, deformations and microstructure evolution during additive manufacturing

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Key Words: *Finite Element, Thermo- Mechanical Analysis, Microstructure, Ti-6Al-4V, Inconel 718*

There are many challenges in producing components by additive manufacturing (AM). One of them is to keep the residual stresses and deformations to a minimum. Another one is to achieve the desired material properties in the final component. A simulation model can be of great assistance when trying to reduce the negative effects of the manufacturing process. A model of the process can even be used to tailor the properties such as microstructure in the AM produced component. Finite element models for predicting the thermo-mechanical response during the AM-process will be presented. This work also features a physically based plasticity model coupled with a microstructure evolution model for the titanium alloy Ti-6Al-4V [1]. The microstructure model is thermally driven and is used to derive the evolution of the non-equilibrium compositions of α -phases and β -phase. The FE-model can be used to evaluate the effect of different welding sequences. Validation of the model is performed by comparing measured deformations, strains, residual stresses and temperatures with the computed result. The residual stresses in the component were measured non-destructively using high-energy synchrotron X-ray diffraction on beam line ID15A at the ESRF, Grenoble [2]. Another application that is classified as additive manufacturing is repair welding. An example of modelling of repair welding will be shown. The material in this example is Inconel 718. The material is welded in aged condition. The welding process changes the microstructure vastly, e.g. in this case the precipitates are dissolved. After the repair weld is performed a local heat treatment by induction heating is conducted in order to restore the strength of the material. To better understand the microstructural changes and to be able to predict the mechanical properties of the material a model for the nucleation, growth and dissolution of the γ'' phase was implemented [3]. The microstructure model is coupled to a physically based flow stress model where the size and volume fraction of the precipitates is one of the main driver for the prediction of the current yield stress.

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Numerical simulation for prediction of residual stresses and distortions for selective laser melting processes of phase-transformation steels

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Key Words: *Additive manufacturing, selective laser melting, residual stresses, finite element analysis*

Selective Laser Melting (SLM) is a promising additive manufacturing technology for production of complex and highly individual parts on short lead time request. Key aspects for the competitiveness of the SLM process are stability and reproducibility. Poorly optimized preprocessing may lead to deviations in structural properties and geometrical accuracy which results in cost and time consuming iterations. Preprocessing assisted by numerical simulations can reduce defects which occur during construction and hence increase the quality of the parts and the efficiency of this technology.

This research work aims to describe a method for a non-linear macroscale simulation to predict residual stresses and distortions for medium-sized parts. It offers an alternative for experimental calibration of faster linear simulation methods [1]. For validation of the method, specimens were fabricated via SLM and subjected to distortion measurements. The investigated materials include one austenitic and two martensitic stainless steels. Numerical simulations with consideration of the material specific phase transformations properties were performed, which show a good agreement with experimental measurements. Significant influence of phase transformations for the residual stresses and distortions were observed. The potential of the method for accurate prediction of the resulting residual stresses and distortion is demonstrated by the comparison of experimental and numerical experiments with various geometry and process parameters.

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A Customizable General Framework for Additive Manufacturing Process Simulation

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Key Words: *AM Process Simulation, Powder Bed Fabrication, mBAAM, Thermal-stress analysis, distortions, microstructure, and final properties*

While significant progress is being made in the last few years, the reliability of AM manufactured parts is often questionable as they often suffer from manufacturing defects and hence subpar strength/fatigue life when compared to parts manufactured with conventional technologies. Sustained experimentation is often required and physics-based computer simulations, like in many other fields before, are sought to provide insight into the process and help accelerate progress in raising the quality of AM parts.

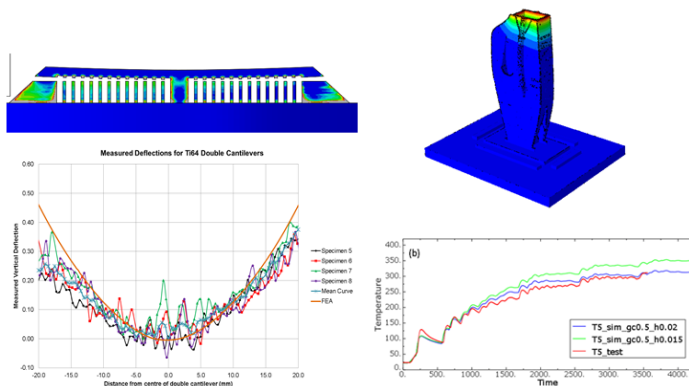
In this work we present a highly customizable general simulation framework for a wide spectrum of additive manufacturing processes based on a thermal-stress general purpose finite element code (Abaqus). The framework allows for: 1) arbitrary meshes of CAD representations; 2) exact specification in time and space of machine tooling (e.g., powder addition, laser trajectories, dwell times, etc.) as would be used on an actual machine; 3) precise tracking of the progressive raw material addition to each element in the mesh via complex geometric computations; 4) precise integration of the moving energy sources (e.g., laser, electron beams, arc welds, high temperature polymer extrusion)[1]; 5) automatic computation of the continuously evolving convection and radiation surfaces, and 6) simulation of a wide spectrum of AM processes such as laser and electron beam powder bed fabrication, direct energy deposition, arc welding, polymer extrusion, ink jetting, etc.

While validated pre-packaged solutions are provided for most common AM processes, we recognize the formidable complexity of the AM multi-physics/multi-scale challenge and hence the need for sustained research in perfecting any given process. For that matter the framework offers an extraordinary level of openness: a) direct and open access to computed outcomes from slicing pre-processing (roller sequence, laser hashing patterns, etc.); b) CAD format for automatically generated support structures; c) large number of APIs related to the “intersections” between the arbitrary FE mesh associated with a part and tool trajectories for

material activation, heating and cooling; d) customizable process parameters definition based on user IP; e) extensive APIs to define customized physics of the material definition, heating and cooling.

The importance of accurate material modelling [2-4] in AM process simulations cannot be underestimated. Therefore the AM simulation framework supports a wide variety of material models relevant to different AM processes, including (anisotropic) temperature-dependent elasto-plastic materials, micro-mechanics-based metallurgical phase transformation models, phenomenological models for grain growth and grain morphology, etc.

Two validated examples are shown: one for SLM powder bed fabrication [5] and one for an mBAAM (metal Big Area AM) [6] wire feed arc welding-based process used for printing very large parts.



From 40 mm bridges to 2 meter long excavator arms: a highly customizable multi-scale/multi-physics/multi-process framework based on a general purpose finite element solver (sample validated predictions).

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Thermo-mechanical model of the Electron Beam Melting (EBM) additive manufacturing process

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Key Words: *Electron Beam Melting, thermo-mechanical, shrinkage effect*

In industry, there is a growing request for increasing flexibility and reducing production costs and lead-time through more efficient and effective manufacturing processes. Additive Manufacturing (AM) technologies have the potential to respond to this request, revolutionising the manufacturing approach [1]. Today, additive processes allow the direct production of complex functional or end-useable metal parts. Among additive techniques for metals, the Electron Beam Melting (EBM) process uses a high-energy electron beam to melt metallic powders and build solid parts, with many applications in the aerospace and medical fields. Hence, EBM is not only a viable alternative to traditional processes but also a process with exclusive benefits. Despite the extensive advantages over conventional technologies, EBM still exhibits several process/part deficiencies. Especially, in order to obtain a defect-free part, beam characteristics, powder properties, and process control should be properly chosen by considering also their interactions. Today an empirical trial and error approach is adopted to identify a suitable combination of process parameters for a given metal powder. Alternatively, process simulation could be a suitable tool for decision-making and process optimization, since virtual analysis facilitates the possibility to explore *what-if* scenarios. Therefore, in order to optimize the quality of the part produced, the research community is studying and modelling the phenomena that occur during the EBM process.

In this work, the pure thermal Finite Element (FE) model on EBM developed by Galati *et al.* [2] was extended in order to develop a thermo-mechanical model that considers the powder-to-solid transition together with mechanical aspects, such as volume shrinkage. The powder layer, that is consolidated after the preheating phase, was modeled as a continuum with an apparent density, lower than the bulk material due to the porosities. In the material change (from raw powder material to melted material) during the exposure, the density increases since porosities are removed. In order to have consistent results, the volume should reduce. It is difficult to implement and instability during solving often occurs in a continuum model, consequently an iterative operation of element removal, adopting the effective approach introduced by Loh *et al.* [3] was adopted, thus reducing the complexity of the model and subsequently computational times (Figure 1). The three-dimensional FE model was developed in Abaqus/Standard and several specific user subroutines were defined. Especially, user subroutines were used to apply heat flux, to move the electron beam spot, to calculate the powder material properties, and to model the thermal expansion/contraction behavior. The effect of the volume shrinkage on the temperature distribution and on the width of the scan line were compared with the results of the pure thermal model and the experimental results given by Qi *et al.* [4]. The comparison showed that the coupled thermo-mechanical approach improved the temperature prediction capability and a good agreement between simulations and experimental data was observed. Moreover, the thermo-mechanical model allowed to evaluate the effective evolution of the track width and the layer thickness after the exposure. The model could be also used to estimate the effect of the

preheating phase on the consolidation of the powder layer, giving an indication on the reduction of the initial porosity and on the effective powder layer thickness after preheating.

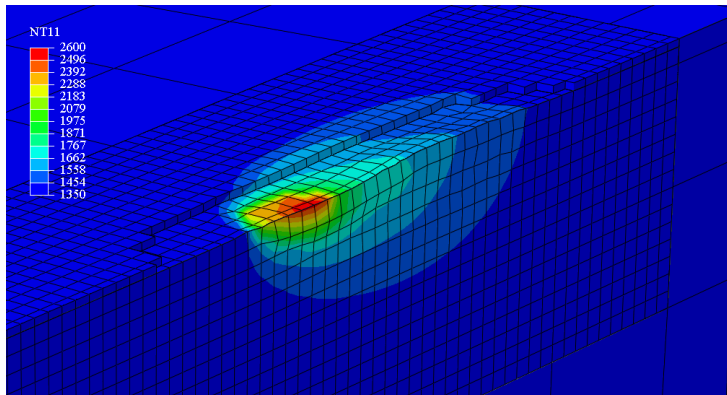


Figure 1 – Volume shrinkage due to the consolidation of the material after the melting phase.

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A free tool for prediction of shape distortions in the AM process that focus on the digitalisation aspects of production planning

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Key Words: *Simulation, Distortion, Thermal analysis, FE-analysis, FOSS, GPL, Python, Production planning*

Additive manufacturing (AM) is a relatively new production process that currently is reaching maturity and thereby acceptance in the industry. Being such a new technology has drawbacks in real production environments. Practically none of the tools that usually are available for production planning exist for the technology today. This makes the production very sensitive to disturbances and very costly. Proper tools that predict process behaviour and connect to production control systems are the key to robust production and needs to be developed.

The dimensions of a component manufactured using the AM technology differs from the CAD drawing (Figure 1). The component might also have inclusions and other faults in the material. Relatively often the component dimensions and integrity are unacceptable and thereby needs to be manufactured again. Since the AM technologies manufactures components layer by layer it takes a long time for a component to be produced in the AM machine and if extra production runs could be avoided the total manufacturing time would be radically reduced.

There exist some commercial codes that try to solve these process related shape distortions. Some examples are Virfac by GeonX (Belgium), Amphyon by Additive Works GmbH (Germany), exaSIM by 3DSIM LLC (US) and Project Pan by Autodesk (US). In academia both Abaqus and ANSYS are popular choices because of their relative openness to user tweaking. The dedicated commercial softwares are commonly not open with what approach that is used for solving the complex temperature-deformation relation. The temperature-deformation relation being the basis of the AM simulation. K. Zeng et al. [4] investigated the state of thermal modelling and came to the conclusion that the FE method is a reliable technique for that. W.J. Seufzer [3] made a literature review of the 10 year effort spent on research on modelling of the AM process. One of the conclusions is that FE-analyses consistently can describe the process, but care must be taken to mesh density and solver. F. Liou et al. [2] used several different analysis techniques to model the AM process with focus on Residual stress and deformation, Solidification,

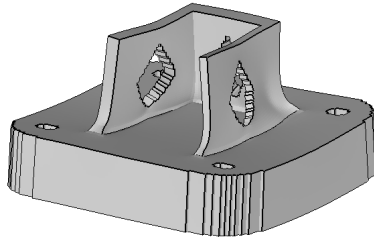


Figure 1: In the AM machine the material is melted and subsequently solidified. This is a process that every time gives distortions. For complex geometries the distortions cannot easily be predicted by rules of thumb.

Microstructure and process monitoring by means of IR camera. For the residual stress and deformation analysis they came to the conclusion that FE-analyses effectively predicts the state in the component. However, a lot of work is needed to capture the complicated situations in industry.

The focus here is to use an approach that is as simple as possible to correctly predict the shape distortion of the AM process and to create a package that is usable for production planning. The software package have some features that makes it a good base for future applications:

- The package is licensed with the GPLv3 licence [1] to ensure the development stays open and thereby accessible for everyone.
- The package encapsulate a smaller part of the AM manufacturing chain into a clear module. Thereby the package can easily be imported into any larger scale AM manufacturing simulation. This is a prerequisite for future control of the process and a backbone for true autonomous systems.
- The package is written in Python which ensures easy development, Python being one of the most adopted languages for scientific computing.

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A multi-level model for the simulation of AM processes

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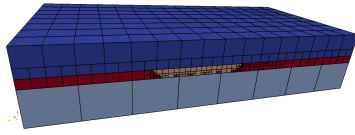
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Key Words: *Additive Manufacturing, Finite Cell Method, hp-FEM*

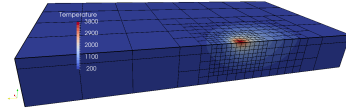
The computational modelling of selective laser melting (SLM) regarding the thermal history and evolution of the artifact produced by this process faces the following challenges besides many others: a highly localized, transient temperature field whose high gradients diffuse away rapidly and the irreversible, non-diffusive phase change from powder to melt. We present a computational model of this process which incorporates the following novelties:

- a) A comparatively low number of degrees of freedom with a comparatively high accuracy. This is achieved by means of the multi-level *hp*-finite element method [3].
- b) A hierarchical treatment of the state variables on a separate, octree-like grid. This *material grid* may refine or coarsen independently of the *computational grids* being used for temperature and deformation fields (see fig. 1). The layer of material does not need to conform to the discretization of the field variables. To this end, the finite cell method is employed which allows for accurate simulations in an embedded domain setting [1]. In case of thermo-elasto-plastic computations as e.g. carried out in fig. 2 the material grid is, additionally, responsible for storing the state variables. We will briefly address issues of handling these history variables in refinement and de-refinement.

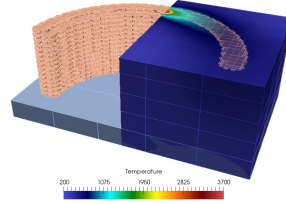
There is yet a fundamental difficulty associated with the initialization of new material layers common to all known approaches, be it the ‘quiet element method’, the ‘inactive element method’ or also our finite cell approach. This is the generation of artificial energy in newly activated regions. For the SLM process, this artifact was reported e.g. in [2] and termed ‘element activation error’. However, the addition of new layers in the SLM process is only one incarnation of the much more general question of how to initialize void regions with appropriate values in evolving domain problems. In case of classical finite elements, newly activated elements must be conformally connected to the old physical domain. They are thus distorted in a general case, inducing unphysical energy in the system. Similarly, the activation of partial cells in case of the Finite Cell Method includes deformation states which were energy free



(a) The material grid: air in darkblue, powder in red, solidified domain in brown and base plate in light blue

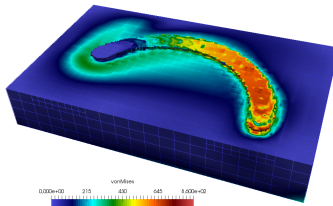


(b) Computational grid (in this case temperatures)

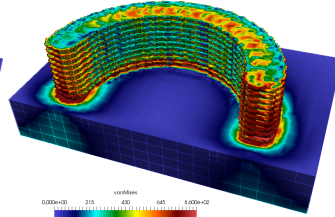


(c) Simulation of an SLM process. The right part of the pictures shows a state of temperature at an intermediate time step, the left part the evolution of the structure due to the phase change from powder to solid.

Figure 1: Separate treatment of state- and field variables



(a) Layer 1



(b) Layer 15

Figure 2: Multi-layer simulation of the residual stresses. left: first layer, right: layer 15.

in the previous time step (as they were ‘outside’) yet produce strain energy after being associated with generated solid material.

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Additive Manufacturing Process Simulation for Large Scale Components

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Key Words: *Additive Manufacturing, Process Simulation, LS-Dyna, Dynamic Mesh Technique, Multi-Scale, Material Modelling*

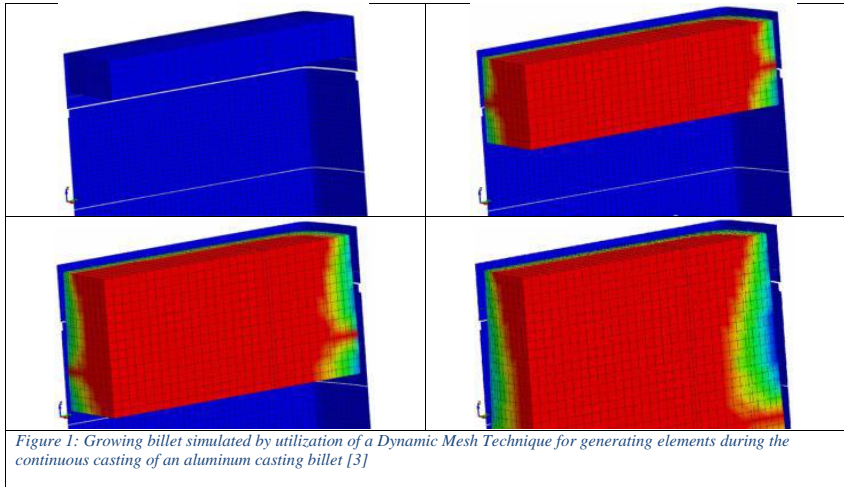
Additive Manufacturing (AM) for metals is continuously and increasingly introduced into workshops as an advanced manufacturing technique for prototyping and small series production. In contrast to established manufacturing techniques, process simulation of AM is still at the very beginning of its development. However, it is crucial for the large scale application of AM to have virtual analysis tools available to simulate these kinds of processes. A process simulation allows for predicting the part's distortion. Consequently product quality is improved and the rejection rate is decreased.

The AM process is characterized by strongly differing scales in terms of time and space [1], as well as the combination of various branches in physics, demanding for multi-physics and multi-scale simulation methods. However, first tools for the AM process simulation have been developed with various limitations of the multi-scale and multi-physics approaches. The applied simplifications often arise from welding simulations, allowing for good correlations between simulation and experimental results, but requesting for big computational efforts.

In contrast to current AM process simulation tools, which have their roots in welding simulation, an approach for AM process simulation will be presented which uses analogies between continuous casting and the AM process. In both processes molten material is added to the top of a growing shape at high temperatures, in both processes the material then solidifies along time at different cooling rates; fast on the outside, slowly inside in the case of continuous casting, and fast for the AM process. In terms of thermo-mechanical process simulation, for both processes layers or lines of elements have to be generated, what can be done by using fixed-grid or moving grid methods [2]. In case of continuous casting the billet grows downwards, in case of AM the 3D-geometry grows upwards. Furthermore, solidification routines and thermal induced shrinkage, damage, and material evolution effects have to be taken into account.

The paper will present the in-house development modules building the basis for AM process simulation within the framework of LS-Dyna. LS-Dyna is running fully thermo-mechanical coupled process simulations, representing a good starting point for additive manufacturing simulation. However, LS-Dyna has to be extended by additional modules for representing the generative process of AM, for consideration of solidification and thermo-mechanical effects and also for material evolution effects at different scales involved in AM such as microstructure development, crystal-plasticity, porosities, fracture or others.

A first extension utilized is the Dynamic Mesh Technique (DMT), allowing for gradual generation of elements (Figure 1). In addition, it is crucial to capture solidification of the molten metal at a level to feed micro-structure models with information about microstructure morphology and distribution time and space dependent. The next module to be included are material models capable of describing the micro-structure and the resulting final material properties (i.e. Flow curves, anisotropy, failure strain etc.) of generative produced components.



Compared to state-of-the-art products for simulating the AM process, the herein described approach will be capable of simulating the production process of large AM components as it originates from continuous casting simulations of aluminum billets where dimensions of up to 7x2x0.5 m are simulated. The framework of LS-Dyna already features a very good scalability [4], allowing for detailed simulations of larger components compared to other simulation tools.

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Parallel finite-element analysis of heat transfer in AM processes by metal deposition

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Key Words: *Additive Manufacturing, Metal Deposition, Powder-bed, Blown-powder, Heat transfer analysis, Parallel finite-element solvers*

In this work the numerical simulation of metal Additive Manufacturing (AM) processes is addressed [1]. In most metal AM systems, a high energy and focused laser melts metal powder or wire to sinter each layer of the object. A layer of added material is created according to the scanning path defined by the user. As a result, a layer-by-layer metal deposition (with titanium, Inconel, steel, or other metals) can be carried out to build complex shapes for components such as turbine blades, aircraft stiffeners, cooling systems, medical implants, among others. The advantage of these kind of processes is the rapid cooling of each deposited layer that results in a finer grain size of the material, if compared to other metal forming technologies such as casting or forming.

The Finite-Element (FE) framework developed to simulate the metal deposition process has already been addressed and experimentally validated for both wire-feeding [3] and blown-powder technologies [4]. However, in the case of powder technologies (powder bed or blown powder), the number of layers to be simulated is much higher than in other technologies, leading to massively large problems that must be dealt with in a computationally efficient manner.

This work enhances the FE framework presented in [4] to run it in a HPC platform. This is achieved by adopting a parallel FE activation technique to follow in time the growth of the geometry driven by the movement of the laser. Moreover, the global linear system of equations is preconditioned with the weakly-scalable Balancing Domain Decomposition by Constraints (BDDC) [2]. The BDDC solver has been implemented in such a way that it can dynamically handle the growth of the geometry in an efficient way. This solution strategy has been implemented in FEMPAR, an advanced high-performance and object-oriented research software. A weak scalability analysis to show the performance of this new framework is shown.

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Thermal FE-simulation of PBF using adaptive meshing and time stepping

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Key Words: *Additive Manufacturing, PBF, SLM, FE-analysis, Bulk Metallic Glass*

Bulk Metallic Glasses (BMG) has the potential to compete with many engineering materials due to their high yield strength, wear resistance, corrosion resistance etc. [1, 2]. They also have the unique property to become super plastic at elevated temperatures and be easily formed to complex shapes, then regain the strength when cooled back to room temperature. However, producing metallic glasses or amorphous structures generally requires very high cooling rates which limits the size of components when using traditional manufacturing techniques. Additive manufacturing using Powder Bed Fusion (PBF) on the other hand enables high cooling rates, which is favorable for glass formation. The current study is part of a project where PBF of BMG will be simulated in order to gain further understanding about the effect of the thermal cycle on BMG.

The additive manufacturing process using Laser-PBF can be very complex and in most cases, multiple experimental trials are needed to trim the settings for a stable building process. In order to determine the structure within a final component, additional destructive experimental methods may be needed as well. Computer aided simulations using the finite element method on the other hand can assist to understand the final structure by predicting the temperature history and thereby, for example if crystallization has occurred during cooling or reheating. Unfortunately, not many models have the ability/capacity to simulate the process due to the large length and time scale differences associated with PBF. Many hundreds or even thousands of layers are typically used to build up AM components, introducing quite a refined computational domain and large models.

The work presented in this paper has resulted in two, individually important models for simulation of glass formation using Selective Laser Melting (SLM). The first is a process simulation model of SLM with high accuracy regarding temperature history during the entire building process, the second is a simplified material model for the glass forming alloy AMZ4.

The process model is a thermal finite element model based on the commercial software MSC Marc and has been equipped with logic for *activation of elements*, *adaptive meshing* and *effective time stepping* in order to in detail, simulate a complete AM process by SLM. The combination of element activation and mesh coarsening enables more or less limitless number of layers to be built while computing the temperature history with high accuracy during cooling.

A cube with equally sides of 9 mm is used as a demonstrator case in this work. Each activated layer has the height of 40 μm , providing 225 layers. Along the activation of each layer is a heat flux boundary

condition defined, representing the laser source as a Gaussian distribution of heat in the vertical downwards direction. In order to increase the efficiency of the model, each layer is activated as one unit. The heating sequence is very short compared to the following cooling time when a new layer is prepared. This time scale difference is accounted for by adapting the time stepping to the temperature gradients such that the cooling sequence can be effectively computed.

The Zr-based AMZ4 material used in this work has a critical cooling rate of about 30 K/s to avoid crystallization. The good glass formability makes this material a great candidate for producing BMG by the SLM technique. The material model contains simple logic to predict glass transformation and crystallization based on the predicted temperature and cooling rate.

The simulation model as shown in Figure 1, provides the thermal history at any position for any given set of process parameters such as heat input (effect, penetration dept, distribution), scanning speed, layer thickness and geometry. The current study is limited to the use of computed cooling rates as indicator whether an amorphous structure is achieved or not.

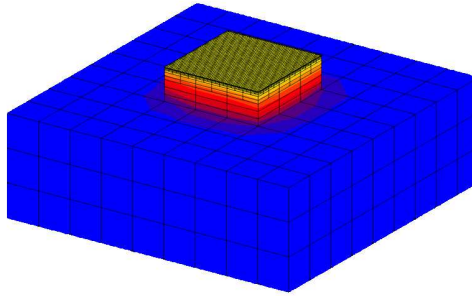


Figure 1: Simulation model showing substrate and a small component (9 mm cube) in progress (loose powder excluded). Refined elements in top layers resolves the thermal history where temperature gradients are large.

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Validation of an approach to reduce simulation time for additive manufacturing

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Key Words: *Finite Element, Thermo- Mechanical Analysis, Inconel 625*

The use of additive manufacturing (AM) increase rapidly today. With traditional manufacturing methods the product is generated by removing material. On the contrary, in additive manufacturing the product is built by adding material layer by layer. This method provides many new opportunities. For instance, the possibility of creating more complex geometries and the possibility of repairing and modifying existing parts. Additive manufacturing can also result in reduced material waste and reduced component lead-time. Before a product can be produced with additive manufacturing, process parameters such as heat input, welding speed, scanning strategy and cooling time must be found. Today this is done mainly by trial and error.

Finite Element (FE) simulations have the potential to replace much of the experimental testing and also increase the knowledge about the process. A thermo-mechanical model [1] can be used to capture the distortion and residual stress that occurs, see Figure 1. Further information is obtained if it also is combined with a microstructure model [2]. This can help in developing the manufacturing process. Process parameters for different cases can be decided with less iterations via the aid of simulations. However, one challenge with simulations is the long computation time. The additive manufacturing process means that many thin layers are added.

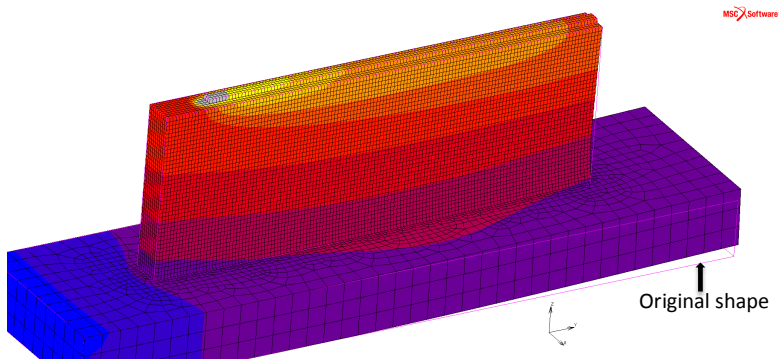


Figure 1. Simulation model. The color range describe the temperature field.

This is especially true for the powder bed method with extremely thin layers. A process may contain many thousands of layers and then it is not possible to resolve the addition of each layer transiently.

In the following presentation the computation time has been considerably reduced for FE-simulations of AM while good results are maintained for the resulting deformation and residual stresses. This result is obtained by using the method of lumping layers. At most the computation time for lumping is reduced down to 5 % compared to a fully detailed analysis. The method of lumping layers means that instead of simulating every string in every layer, many strings and layers are merged and added simultaneously. The method has been studied thoroughly where strings have been lumped in height, see Figure 2, lumped side by side or both. As a consequence of lumping layers and strings the elements can also be merged and thus represent many layers. The simplifications lumping involves make that some details may be missed but the overall behavior is captured. So therefore the usability of the model depends on what the aim is with the simulation and what result that is sought for.

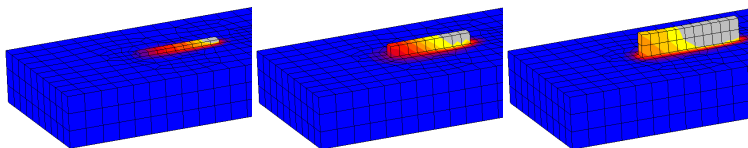


Figure 2. Simulation models. No Lumping(left), lumping 3 layers (middle) and lumping 6 layers (right).

The simulations are validated against experiment [3] with good agreement. The experiment, where the material was the nickel based super alloy Inconel 625, was performed with directed energy deposition (DED) where metal powder is blown onto the part and melted with a laser beam. The method is not restricted to modelling of the DED process. Processes where the material is added via wire should work equally good. Future work will include the usage of this method in the modelling of the powder bed fusion process.

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Efficient three-dimensional simulation of fused deposition modeling by coupling finite element and boundary element analysis

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Key Words: *additive manufacturing, boundary element method, contact mechanics, creeping flow, finite elements, fluid structure interaction, fused deposition modeling, liquid membranes, stokes flow*

Extrusion-type additive manufacturing processes like fused deposition modeling are commonly used for the rapid creation of three-dimensional objects. In these processes, a molten polymer is deposited at prescribed positions to solidify there. In this way, an object with the desired shape is built layer by layer from the bottom up. Numerical simulations can be employed to improve the comprehension of the fused deposition modeling process. Thereby, the required amount of material, time and energy can potentially be decreased while more accurate and stable products can be produced. Several mechanical and thermal phenomena have to be considered in such a simulation: Fluid mechanics within the polymer, fluid-structure interaction between the polymer and its surface, thermomechanical contact between molten polymer, solid polymer and the rigid substrate, heat conduction within the molten polymer and the resulting solidification.

A new method is presented to model three-dimensional fused deposition modeling by coupling finite element (FE) method and boundary element method (BEM). Liquid droplets that are governed by their surface tension are efficiently modeled with an FE formulation for liquid membranes [1, 2]. This formulation also allows the consideration of polymer-polymer and of polymer-substrate contact and the resulting bonding. Furthermore, the presented method also takes the motion of the molten polymer into account. Since Reynolds numbers are typically very low in fused deposition modeling, fluid dynamics can be described by the linear Stokes equations. Stokes equations are solved with the BEM, which only requires boundary discretization. Since volume discretization is also avoided for the FE membrane formulation, the dimension of the whole method is reduced. Consequently the computational as well as the meshing effort is highly reduced.

The BEM is also suitable to model heat conduction and (linear) elastic deformations. Therefore, the presented method can be extended to the whole additive manufacturing process including melting of the polymer in the extruder nozzle and its solidification on the substrate.

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LBM-specific direct solver strategy for the quasilinear heat equation

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Key Words: *laser beam melting, direct solver, quasilinear heat equation*

Laser Beam Melting (LBM) is increasingly used in the production process [5]. However, the process inherent high temperature gradients lead to distortion of the part. In order to reduce the necessary iteration cycles of manufacturing, measuring and subsequent pre-deformation of the geometry, simulation models are used to predict distortion and residual stresses [1]. The different time and length scales in laser beam melting [3] result in high computational effort. In addition, non-linear material parameters are used due to the large temperature differences from solidus to room temperature. Beside modeling approaches [2], the adaption of numerical methods [4] holds a great potential to accelerate the calculation.

The simulation of LBM has some specific requirements compared to general simulations, e. g. the layer-wise mesh and the growing system of equations during the simulation. Since these conditions are clearly known, the knowledge can be used to speed up the calculation.

An LBM-specific direct solver will be presented which takes advantage of the special structure of the matrices in order to consider the enlargement of the system. The stiffness and mass matrices will be modified by shifting the integration points to the representative node of each test function. In consequence, the matrices can be decoupled from the temperature-dependent material parameters. This enables the reuse of the Cholesky decomposition of the matrices for multiple time-steps. Together with this, an algorithm was developed to consider the activation of new layers. The decomposition effort is reduced to the additional equations and the coupling matrices with the already decomposed system.

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The successive node-snapping scheme to generate conforming meshes for additive manufacturing simulations

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Key Words: *Successive Node-snapping Scheme, Additive Manufacturing*

Additive manufacturing, including 3D printing, has attracted widespread attention due to its ability to manufacture complicated shapes for mechanical, aeronautical, and biomedical applications. Efficiently meshing the part being printed taking into account the additive layers remains a challenge for the numerical analysis, such as heat and mechanical analysis. We address this challenge by developing a meshing scheme by snapping selected nodes of a fixed background mesh to the boundary of an evolving domain [1], in this case the already printed part. In this conference I will present the current status of the work, including examples of meshing a partly printed ellipse, as shown in Figure 1.

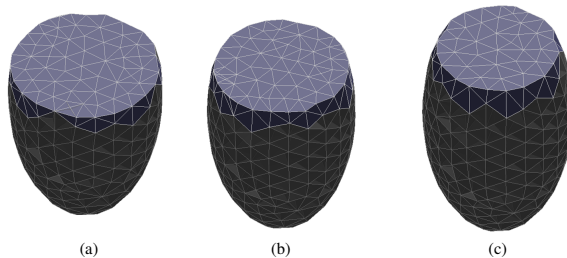


Figure 1: Meshes of slide models for an ellipse being 3D printed.

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Development of a simulation framework for AM process consideration in industrial production

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Key Words: *metal additive manufacturing, grey-box model, FEM*

AM technologies are widely known as the future of the manufacturing industry, thanks to their possibilities in terms of shape design, minimum lot sizes, and material efficiency [1]. Moreover, since tools and fixtures are not required, a significant reduction in time and cost can be realized [2]. However, in the aeronautical sector, the AM penetration degree is still limited due to its novelty and lack of production experience. AM technologies are considered premature for industrial production: numerous process parameters directly influence the final material properties, geometry and tolerances, but the relationships between process conditions and final properties are not easily understandable, being phenomena involved in AM processes very complex [3]. To achieve low defect and dimensional conforming functional part fabrication, optimal process parameters and best supports/orientation are required and currently, in order to avoid distortion and defects, an experimental trial and error method is typically used across a range of process parameters and manufacturing configurations [4]. This approach is time consuming and may not include all the process parameters and configurations of interest, because the experiments are expensive. To avoid the trial & error approach, a set of verified computational tools should quickly test several processes manufacturing alternative combinations. This would greatly aid the maturation of AM techniques.

The present work is focused on grey box models, incorporating physical relations and experimental knowledge with accurately designed approximation levels, since they are the most promising tools for a higher penetration degree of AM techniques in the aeronautical industry. Thus, a commercial general purpose software (Abaqus 2017) is enriched with dedicated subroutines and user functions to model the AM process physics, in order to develop a flexible framework for the simulation of different AM processes for metals. It is based on finite element (FE) numerical method, taking into account melt pool dynamics and the interaction between heat source and raw materials. The simulation is tested and validated on diverse processes involving different heat sources and materials (powder bed fusion, direct energy deposition, ...). The output of the grey-box model in terms of melt pool geometry, solid-state transformations during the heating and cooling process, and residual stresses could be effectively employed in order to support the optimization of the AM process. Moreover, the outcomes of the models will also be at the base of a macro-scale modelling.

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Thermal analysis of the laser beam melting process based on high order discontinuous Galerkin method

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Key Words: *Additive Manufacturing, LBM, Discontinuous Galerkin Method, Thermal simulation*

Additive Manufacturing technologies for metallic components such as the Laser Beam Melting present some shortcomings in terms of quality assurance, in particular when the mechanical properties are critical and need to be guaranteed. For example, porosity and cracks may be present in dense materials produced by AM. One of the key elements that directly influences the part quality is the ability to control the temperature of the powder bed during the process. The heat balances between the energy input of the laser beam and the heat conduction within the part, the powder and heat losses.

To this end, a numerical model for transient thermal analysis of the Laser Beam Melting process has been developed focusing on a good compromise between solution accuracy and computation time. This model gives access to the thermal history in any point of the manufactured part or powder bed, without approximation on thickness of the powder layers or the laser path. During the simulation, the progressive activation of the different layers of powder is performed by successive mesh generations. Consecutive meshes are generated by maintaining equivalent number of elements for less memory consumption.

The numerical strategy for the thermal problem discretization builds on the variable high order discontinuous finite element method. The interpolation order is distributed with respect to the additive manufacturing progress during the numerical simulation. The thermal analysis accuracy is improved by using high interpolation order in high thermal gradient area. The discontinuous Galerkin approach is well suited for distributed parallel computations due to its good scalability related to the typical block sparse matrix structure.

The laser beam is modeled using a moving equivalent heat flux that is linearly distributed along the laser path. This distributed heat source greatly reduces the large computation times compared to models with very localized heat flux using an energy distribution similar to the one of the laser beam. This results from the lower number of time steps needed to simulate a continuous displacement of the laser beam. A comparison between both approaches is illustrated and shows very similar temperature distributions.

This methodology will integrate an adaptive variable interpolation order following the heat source trajectory. This feature will potentially maintain solution accuracy and reduce computation cost.

In this study, 3D simulation results for the Laser Beam Melting process are presented for the construction of a solid part whose section evolves along the build direction. The temperature field computed at the surface are shown at different instants during the LBM process for a part made from Ti6Al4V powder. Simulation results are compared to experimental measurements made with an infrared camera.

Computer Aided Tools for Additive Manufacturing based on an Isogeometric Approach

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Key Words: *CAX for Additive Manufacturing, Isogeometric Analysis, Interoperability*

The challenges of geometric representation for Additive Manufacturing are many. Material properties can vary through the object and lattice structure and internal voids can be used to improve the product performance. State-of-the-art CAD-tools, are not well suited for Additive Manufacturing as they are based on boundary structures where a solid object is represented by the surfaces of the inner and outer hulls of an object. The boundary structure approach was developed more than 3 decades ago to support design for subtractive/abrasive processes, processes that incrementally remove material from a solid block of raw material.

IsoGeometric Analysis (IGA) was introduced in 2005 by prof. Tom Hughes [1] to bridge the gap between CAD and Finite Element Analysis. The shape functions of finite elements were replaced by B-splines, introducing higher order continuity between elements and near exact reproduction of all CAD-shapes. However, going from boundary structure CAD models to 3-variate B-spline based IGA-models is similar in complexity of going from CAD-models to FEM-models. This triggered research into 3-variate B-spline/NURBS based CAD-models that could be directly used in IGA. 3-variate B-spline/NURBS based CAD-models allow the description of continuously varying properties inside an object. This can be done through addition 3-variate B-spline functions representing the desired properties. These functions are connected to the geometry through a shared parametrization.

For objects to be built from multi materials, it is easy to see that such fields can be used for specifying the material mixture imitating RGB in colour representation. However, these fields also have a potential to be used as parameters for procedural generation of lattice structures: Required density; required geometry or property anisotropy, etc.

The CAXMan-project [2] addresses analysis based design for additive manufacturing using the representations and approach of IsoGeometric Analysis, taking aspect of additive processes into consideration already during design. The approach builds on the extension of ISO 10303-209 edition 3 [3] with respect to IsoGeometric Analysis and locally refined splines. The talk will address the approach of CAXMan and present results achieved. The CAXMan project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680448"

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Fast Numerical Simulation of Residual Stress in Laser Beam Melting of Ti6Al4V

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Key Words: *Laser beam melting, Residual Stresses, Numerical simulation*

A fundamental challenge in laser beam melting of metals is the development of residual stresses. This can lead to different issues during the process like crack formation, distortion and process terminations or to the decreasing mechanical properties, in particular fatigue strength. As the process is highly complex in terms of interacting parameters and truly expensive, when intensive experimental studies are conducted, the numerical simulation has become an important tool to analyze residual stresses and their effects on part distortion. Several transient, mainly coupled thermomechanical approaches have been developed [1]. However, those methods are long lasting and in consequence due to computational power limitations, restricted to small parts, which are modelled by low numbers of finite elements [2].

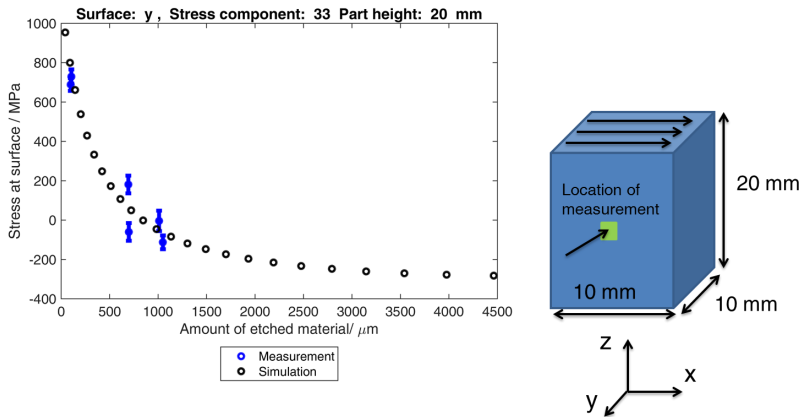
The recently developed finite-element approach of so called “mechanical layer equivalent (MLE)”, which is based on the concept of inherent strain [3], delivers an auspicious approach for fast prediction of part distortion [4]. In this method, a mean inherent strain tensor, which is caused by the cooling of a recently exposed layer by a specific scan pattern, is deducted from mesoscopic simulations or experimental studies. Afterwards, this strain tensor is used as the driving force formulated as a load in the successive calculation of the mechanical equilibrium state in layers.

As the part distortion is an easy measurable quantity, the model has been used on the calculation of part deformation so far and good accordance has also been obtained using this approach [4]. However, residual stresses have not been assessed directly by the MLE-method. Generally, only few attempts have been conducted on simulation of the residual stresses in laser beam melting, whereby the method of residual stress measurement by neutron diffraction has been found to be an encouraging approach for further studies [5].

In order to analyze the power of the MLE-method in prediction of residual stresses, cubic test samples (ground section: $10 \times 10 \text{ mm}^2$, height: 10 – 20 mm) have been generated using laser beam melting from the titanium alloy Ti6Al4V. Two different scan strategies, namely a bilinear scanning and a bilinear scanning with 90 degree rotation between layers were used. The residual stresses on the surfaces have been measured by X-ray diffraction. In order to investigate the residual stress evolution in the depth along certain paths on varying faces of the cubic samples, layers of a thickness up to 1500 μm were removed by electrochemical etching and residual stresses have been successively measured on the new surfaces. However, it is known that the material removal can lead to considerable changes

of the residual stress state and this effect has to be taken into account. Analytical models exist for simplified cases which can be used to correct the data, but the obtained results can be more or less erroneous. Another approach, in order to achieve a reliable comparison of the measured values with the simulation results is to simulate the layer removal in the numerical model as well, by deactivation of the finite elements.

The results show very good agreement of measured and simulated values across all measured stress components and surfaces. Based on these results, the MLE-Method could be validated what confirms that this method can be used as valid model for fast prediction of residual stress in laser beam melting processes.



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Semi analytical solutions and experimental investigations on optimal process parameters for selective laser melting

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Key Words: *Selective laser melting, analytical solution, focus offset*

The quality of parts manufactured by selective laser melting (SLM) depends on different process parameters, like laser power, scan velocity, focus diameter and powder distribution. Therefore, the determination of optimal process parameters plays a key role for the quality of the building process. Numerical simulations are widely applied for SLM process in order to find optimal building parameters. See for example [1, 2, and 3]. They allow take into account physical processes, materials properties and their temperature dependencies, but usually require long-time-computations.

Fast estimations of optimal parameters can be performed on the basis of relatively simple semi-analytical models, which provide quite satisfactory results for welding track depth and width and their dependency on laser power, scan speed and laser focus diameter. Semi-analytical models are also very useful for fast testing of the influence of thermo-dynamical properties of material such as heat conduction coefficient or heat capacity on the parameter of build process.

In this paper the semi analytical solution for a moving single ellipsoidal heat source [4] and the analytical solution for a fast moving heat source [5] are used for fast estimations of SLM process parameters.

In order to validate results of simulation a series of experiments are conducted. A deep penetration effect is clearly observed in the micro-welds by the lower scanning speed. The example of comparison of semi analytical calculations with experimental results for two different scanning speeds is shown in Fig. 1.

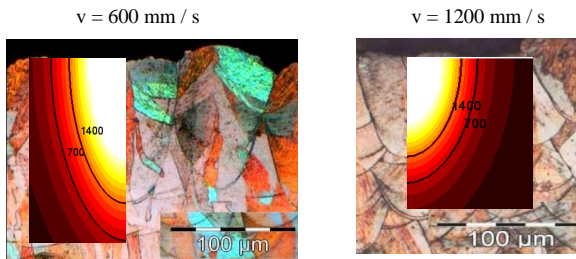


Fig1. Comparison of semi analytical calculations with experimental results

Variation of the laser focus offset leads to the transition from the heat conduction modus into the deep penetration modus of micro-welding. The results of experiments are in a good agreement with theoretical estimations of the transaction energy density.

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A Computationally Efficient Process Modelling Approach for Selective Laser Melting

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Key Words: *Additive Manufacturing, Selective Laser Melting, Process Modelling*

Selective laser melting (SLM) is one of the main additive manufacturing methods suitable for metallic parts. Since SLM has nearly no limitation in terms of geometrical complexity, it enables manufacturing products which cannot be produced by traditional manufacturing techniques. However, a critical issue in SLM is the undesired deformations and residual stresses which arise due to the non-uniform thermal gradients introduced by the laser scanning process.

We present a computationally efficient thermo-mechanical model to investigate the development of deformations and residual stresses during the build for a range of SLM process parameters and various scanning strategies. A semi-analytical thermal model is used to predict the temperature evolution, in which an analytical solution is utilised to capture the steep temperature gradient in the vicinity of the laser, and a complimentary temperature field solved numerically is used to account for the boundary conditions. Since the steep temperature gradient around the laser is accounted for using an analytical description, a coarse spatial discretisation can be used for the numerical solution of the complimentary temperature field.

The temperature field is then used to calculate the thermal strain induced on the SLM product. Corresponding elastic and plastic deformations and stresses are calculated using a temperature dependent elastic-plastic material model with kinematic hardening. The melting behaviour is taken into account by setting the stress and strain to zero when the temperature exceeds the melting point. The mechanical analysis is assumed to have little effect on the temperature field, thus the thermal and mechanical models are one-way coupled. The proposed model is able to describe the development of temperature, associated deformation and stress-strain state within the product during the SLM process.

Case studies for building one layer and multiple layers are investigated. For the one-layer-building process, the influence of different scanning strategies on the residual stresses distributions are studied. The thermal and mechanical simulations are compared with experiments and other simulation results in literature [1]. Next, a block built by multiple layers is simulated and the predicted residual stresses are compared with the experimental results in literature [2]. Good agreements in both cases validate the accuracy of the proposed model.

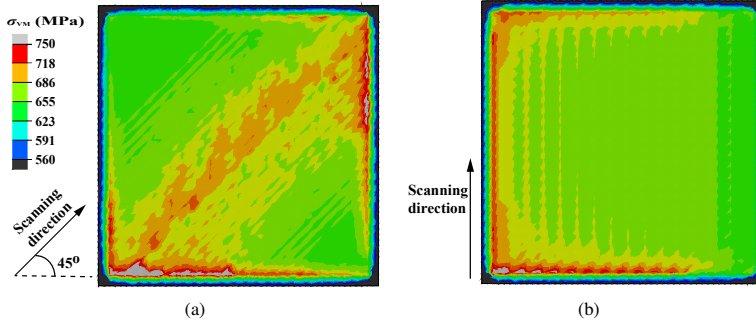


Figure 1: The von Mises stress distribution after building one layer with two different scanning directions. (a) The scanning direction is 45° degrees with respect to the horizontal direction. (b) The scanning direction is along the vertical direction.

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A Semi-analytical Thermal Model of Selective Laser Melting Process

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Key Words: *Additive Manufacturing, Selective Laser Melting, Thermal model*

Selective laser melting (SLM) is one of the most widely used additive manufacturing technique suitable for metallic materials. In SLM the product is fabricated in a layer-by-layer fashion where a laser beam is scanned over the powder bed to selectively melt and fuse powder particles according to a predetermined pattern. SLM can produce metallic components with complex geometry while creating virtually no porosity. However, SLM products suffer from substantial deformation and residual stresses that arise due to heating/cooling cycles and the associated thermal strains introduced during manufacturing. It is experimentally well established that not only SLM process parameters, but also the laser scanning strategy and the topology of the product have a substantial effect on the temperature transients of the part and henceforth on the degree of deformations and residual stresses [1]. In order to investigate the influence of the scanning strategy and part geometry on the temperature history of a part, temperature evolution during the process should be modelled while accounting for the moving laser spot. Temperature can achieve very high values in the vicinity of the laser and drops down abruptly with the increasing distance to the laser. As a result, steep temperature gradients are observed around the laser spot, with a dimension on the order of tens of micrometres. On the other hand, product has dimensions on the order of tens of millimetres. Therefore, in a numerical model, in order to capture the local high temperature gradient around the laser, a fine discretisation is required in the spatial domain, which in turn makes the model computationally prohibitive. Although some simplified thermal models [2, 3] are proposed, they all neglect the effect of the laser scanning history. As a result, these models are incapable of accounting for the influence of the scanning strategy.

A semi-analytical thermal model is presented to fill the gap between the efficiency and accuracy in predicting the temperature evolution in SLM process. The moving laser spot is represented with a finite number of point heat sources, which are activated at different time instances. An analytical temperature field is obtained first by summation of all the temperature fields due to each individual heat source in a semi-infinite space. Then the temperature field of the built part is constructed by the superposition of the analytical temperature field and a complimentary field which accounts for the boundary conditions. The steep temperature gradient is mainly captured by the analytical field and the complimentary field is solved numerically. The proposed model enables to decouple the numerical discretisation from the steep gradients in the temperature field associated with the localised laser heat input. Consequently, an

accurate and numerically tractable simulation of the process is achieved. The accuracy of this semi-analytical model is validated by experiments. Case studies for building a complete layer using two different scanning strategies and subsequently building of multiple layers with constant and rotating scanning patterns in successive layers will be presented.

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Simplified numerical methods for distortion prediction in Selective Laser Melting and their experimental validation

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Key Words: *SLM, Detailed Transient Analysis, Inherent Shrinkage, Inherent Strain*

In metal additive manufacturing (AM) by Selective Laser Melting (SLM) parts are built on a layer by layer basis by applying a focused power source (laser or electron beam) to the powder material which is rapidly heated above its melting temperature and then allowed to solidify and cool down to form a new solid layer. Typically, this manufacturing process induces residual stresses and distortions, which may be critical to accomplish with the required manufacturing tolerances. In this regard, a priori prediction of these distortions at design stage is preferred to the trial and error strategy commonly employed to optimize the fabrication process.

The detailed transient thermo-mechanical analysis (DTA), widely used for high-fidelity simulation of the AM processes ([1], [2]), is commonly considered as the reference modelling strategy. However, several simplified numerical methodologies based on the finite element method have been developed to overcome the large computational time required by DTA. The inherent shrinkage method [3] and specially the inherent strain method [4] are the most suitable methods within this approach.

This work copes with the analysis, developments and applications of the aforementioned simplified methodologies for the prediction of the final distortions in powder bed based SLM process. The main objective is to compare these approaches with the results obtained by the DTA analysis as well as with the experimental evidence obtained by SLM manufacturing. The accuracy of those methods is discussed.

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Immersed interface Discontinuous Galerkin method for additive manufacturing thermal analysis

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Key Words: *Additive manufacturing, Immersed interface, Discontinuous Galerkin, thermal analysis*

The additive manufacturing finite element modeling requires special procedures to represent numerically the addition of deposited material. Basic approaches are possible such as successive mesh generation including geometrical evolution and element activation techniques, the most famous of which are “quiet element method” and “inactive element approach”. For this study, to avoid drawbacks of remeshing cost and ill-conditioning system, the material addition modeling is handled by a specific embedded method : the immersed interface approach.

A transient finite element model for the thermal analysis of general additive manufacturing processes has been developed using a high order extended Discontinuous Galerkin (DG) method [1]. A Level-Set function is used to capture the interface and an enrichment technique will enable to treat sharply the discontinuities inside cut cells. By using this method with DG discretization, the convergence order is kept in the vicinity of the interface. In addition, the discontinuous character of this DG immersed interface method allows an efficient local treatment of the cut cells [2].

In this work, a sharp interface method is integrated into a three dimensional high-order DG code Argo [3]. The extended solver can treat the heat diffusion problem over an immersed domain with explicit or implicit time integration. The spatial integration over cut cells is handled using the hierarchical moment fitting technique proposed in [4]. The agglomeration of small cut cells proposed by [5] has been proven to be essential for the stability of the scheme. The robust implementation allows to treat and to stabilize the computation for heat diffusion problems with moving interface in the framework of additive manufacturing thermal modeling.

In this study, 2D and 3D simulation results are presented for a solid part whose section evolves along the build direction following an additive manufacturing process. The temperature field is computed at several times during the process. Metallic powder is deposited on the sample and melted by an heat source to build layer by layer the final part. Simulation results from DG immersed interface model are compared and discussed with results of thermal analysis based on successive conform mesh generation.

This work is a first step towards a hydrodynamics model for additive manufacturing processes. The extended solver can treat a multi-physics and multi-phases problem over the immersed domain. The immersed interface method can guarantee locally the complex interface tracking induced by multi-physic phenomena during the process.

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AM PRODUCT SIMULATION

Continuous Verification and Validation for the Simulation of Distortion in Laser Beam Melting

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Key Words: *laser beam melting, verification, validation, distortion, residual stresses*

With Laser Beam Melting (LBM) transitioning from providing prototypes to production parts, the requirements in terms of process reliability and accuracy are increasing. Due to steep spatial and temporal thermal gradients, stresses are introduced during the build process that ultimately result in distortion [2]. Depending on the required shape accuracy and the geometry of the individual part, this distortion may exceed given tolerances during or after the build process, possibly resulting in build cancellations or geometry and/or support adjustment and an additional build job, respectively. In order to predict and avoid these both technically and economically disadvantageous occurrences, multiple commercial and research-oriented simulations models of the structural behavior of additively manufactured parts are developed. However, the benefit of such a model is determined by the likelihood of it being respected in a decision-making process. And this, in turn, is dependent on the model maturity and thus, among others, on the applied techniques of Verification and Validation (V&V) and the amount of respective data [3]. To this end, the application of software engineering methods and tools related to Continuous Integration [1] to the V&V of simulation models is suggested. Additionally, suitable techniques for an LBM simulation model are selected and exemplary results are presented.

The workflow for the development and implementation of simulation models is typically similar to that of software engineering projects. Code is incrementally developed, modules are added to in this case e. g. incorporate necessary physical effects, and test cases are being defined both on the level of modules and the system as a whole. In contrast to most software projects, however, simulation models oftentimes require user interaction or their parametrization is difficult to access, prohibiting or hindering the usage of automatic testing.

The potential benefits of code adjustments to allow for an automated execution are thus presented for simulation developers and users to decide whether the additional effort may represent a positive return on investment. With an automated execution, tools that are used for continuous integration in the software engineering domain, can be applied to pave the way for an automated way for a CV&V.

The V&V of simulation models is well established in literature and schemes of differing levels of complexity are used to describe the relationships between, at the least, the problem entity, the conceptual as well as the computerized model. See Figure 1 for a clear and tangible scheme. [4].

Therefore, only existing techniques are screened for their suitability of CV&V in the context of LBM simulation. The first step of translating the occurring phenomena into a conceptual model is not directly

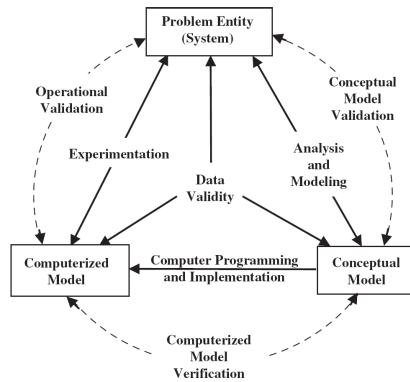


Figure 1: Schematic of the relevant elements of V&V [4]

accessible for automatic testing. This stage of the V&V process is dominated by human expertise. For the computerized model verification stage, i. e. the formalization of the conceptual model on the other side, numerous methods starting with simple unit tests and ending with e. g. regression testing, degenerate tests and operational graphics are applicable. Similarly, the comparison to real life data, the validation stage, can also be done in automatic way after suitable data has been collected. However, in all of these stages, special care concerning data validity is necessary. Thus, typical sources of error are discussed and possible alleviation strategies are presented.

The presented methodology and techniques are intended to serve as examples on how to increase the credibility and reliability of simulation models of the LBM process for both the users and the developers.

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Simulation of Hydrogel Reinforced by 3D Printed Fibres

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Key Words: *fibre-reinforced hydrogels, 3D printed fibres, additive manufacturing product simulation*

Fibre-reinforced hydrogels offer an attractive pathway towards the mimicry of soft tissues. Herein, 3D printed micron-sized fibres are used to reinforce a hydrogel. Resulting bio-inspired soft matrix composites are shown to be flexible yet stronger than their hydrogel alone counterparts.

The non-trivial interaction between fibres and gel determines the material properties of the composite structure. A large set of parameters (as fibre diameter, shape, distance, crossing angles, etc.) can be used to approximate mechanical attributes of a soft tissue. This optimization procedure can be effectively supported by means of computer simulations, significantly reducing the effort for physical production and testing. We present how to model and simulate hydrogel reinforced by 3D printed fibres using a high-order Finite Element Method (FEM). This technology is well suited to handle complex geometries, allows a direct treatment of nearly incompressible materials and supports very large aspect ratios of elements, so that the typically long and thin printed fibres can be discretized with a low number of degrees of freedom. The simulation results are finally validated against physical tests, showing the suitability of the suggested approach.

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Numerical simulation of material parameters of additively manufactured porous metal parts

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Key Words: *Additive Manufacturing, Numerical Homogenization, Porous Media, Finite Cell Method*

Selective Laser Melting is a well-known variant of additive manufacturing. It offers the possibility to design porous, lattice-type structures with desired mesoscale structure properties by varying the hatch distance and the laser scan direction. The porosity of such materials may be exploited e.g. in the design of next-generation gas turbine blades using transpiration cooling. However, the mechanical properties of these new type of materials must be estimated carefully prior to the built process to assure the quality of the finished parts. However, for these structures, analytical homogenization strategies fail as the characteristic mesostructural length scale (i.e. the diameter of the solidified melt pool) becomes comparable to the macroscopic one.

Numerical homogenization techniques in combination with the Finite Element (FE) Method provide an efficient alternative to the conventional approach. A difficulty of FE analysis is its necessity to resolve the topologically complex graded lattice structures in a boundary conforming manner — a procedure which is not easily automatable in a robust manner. To address this issue, we utilize the Finite Cell Method [1] for the numerical homogenization of the mesostructure and employ the window method [2] to determine the effective material properties. We will demonstrate by various examples that the combination of these two approaches is an efficient technique and present a road map of an automatized numerical determination of the elastic mechanical properties of graded lattice structures.

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Inclusion of AM Process Simulation within the Defect Tolerant Fatigue Design Concept of SLM Manufactured Components

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Key Words: selective laser melting, SLM, additive manufacturing, AM, fatigue, geometric accuracy

The selective laser melting (SLM) process is prone to porosity, defects arising from lack of fusion, thermal stresses (including residual stresses), and irregular surface quality. These factors have a significant combined effect on the fatigue strength of components produced with this manufacturing technique. The adjustments to the SLM process parameters and additional post-processing procedures necessary to improve the fatigue strength of the printed components also tend to increase build time and manufacturing cost [1-3]. This situation is similar to that of casting design, whereby assuming a defect-free casting in fatigue dimensioning would lead to expensive manufacture of such components. Instead, the standard practice in castings is to allow for the existence of manufacturing and material defects at e.g. low stress regions of the component and revise the design based on casting simulation and structural optimization. A similar approach can be utilized in the design of SLM components. An overview of the proposed defect tolerant fatigue design concept for the SLM process is illustrated in Figure 1.

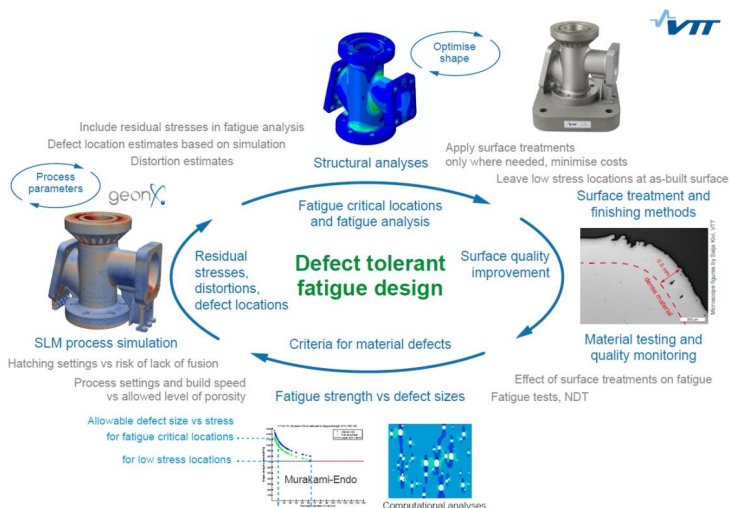


Figure 1. Defect tolerant fatigue design concept for use with SLM manufactured components [4].

The numerical simulation of the SLM process and post-treatments has been identified as a key component in the workflow. The ability to obtain estimates of the thermal stresses, distortions and defect distributions in the manufactured component early in the design phase is crucial for enabling the designer to create a part that meets all specifications and is manufacturable at a reasonable cost. The goal of the present paper is to investigate the use of commercially available SLM process simulation software for prediction of thermal build-up during printing and geometric accuracy of the final component.

A challenging geometry was chosen for study (Figure 2) that includes design features suitable for SLM (e.g. self-supporting elliptic cross section of horizontal pipes, added ribs and local details to make overhanging members self-supporting), and features such as thick sections and overhangs that are challenging to manufacture due to thermal distortions [4]. The component was manufactured using optimized process parameters for the materials used. During manufacturing, time-lapse video and thermal imaging were recorded, and after printing a FARO laser scanner was used to determine the geometric accuracy of the printed components as compared to the CAD model. Commercially available AM process simulation software was used to predict thermal build-up of the part during printing, predict cases where build failure would occur, and determine the geometric accuracy of the built component before and after post-processing procedures. Simulated and measured results are compared and discussed, along with plans for uptake of these methods within the defect tolerant fatigue design concept.

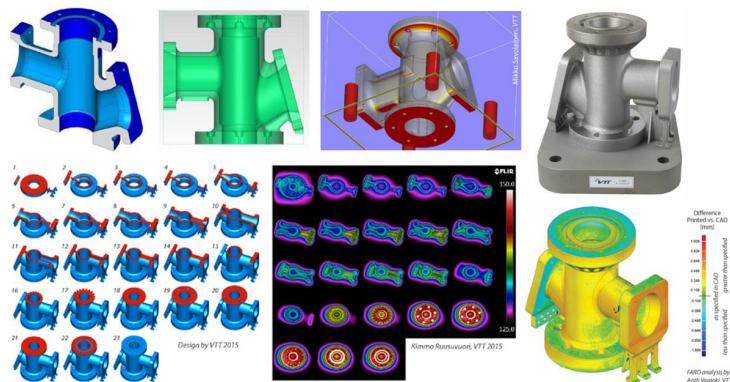


Figure 2. Images of test component CAD geometry, thermal imaging during printing, final printed component, and FARO geometric accuracy measurement.

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Finite Element Modelling of Composite Materials Parts Produced by Additive Manufacturing

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Key Words: *LS-Dyna, Mechanical Behavior, 3D printing test specimens*

In this work is presented a methodology for the finite element modelling of a test specimen shown in figure 1, being the specimen produced by Additive Manufacturing (AM) of thermoplastic reinforced by continuous fibers. The objective is to simulate in LS-Dyna the mechanical behavior of the specimens in tensile, compression, bending and torsion according to standards [2] to characterize the anisotropic properties associated with this type of composite materials parts obtained by three-dimensional printing [1].

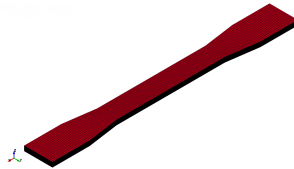


Figure 1: Test specimen

In this work are simulated the experimental tests performed by [3], where a set of tensile tests on printed samples using Fused Deposition Modelling technology using Nylon filaments and a continuous Kevlar fibre reinforcement in the layer arrangement. The cross-section of the test specimen is represented in figure 2, and the mechanical properties of the Nylon and the Kevlar are presented in tables 1 and 2, respectively.

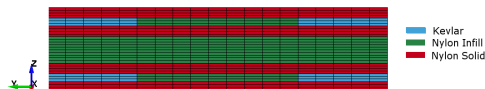


Figure 2: Cross-section of the test specimen

Property	Value
Elastic Modulus (E)	3.5 GPa
Shear Modulus (G)	1.3 GPa
Poisson's ratio (ν)	0.35

Table 1: Mechanical properties of the Nylon (adapted from [3])

Property	Value
Longitudinal Elastic Modulus (E_{f1})	79.8 GPa
Transverse Elastic Modulus (E_{f2})	2.59 GPa
In-plane Shear Modulus (G_{f12})	1.3 GPa
Poisson's ratio (ν_{12})	0.33
Poisson's ratio (ν_{23})	0.1

Table 2: Mechanical properties of the Kevlar (adapted from [3])

Simulations are conducted for the various reinforcement volume ratios tested in the experimental trials, considering important aspects in the numerical modelling of composites materials such as the direction of the fibres, represented in figure 3, and the cohesion laws between the different layers. These models can be further used with optimization methodologies to reach lightweight designs with improved strength properties that can be achieved with this manufacturing process.

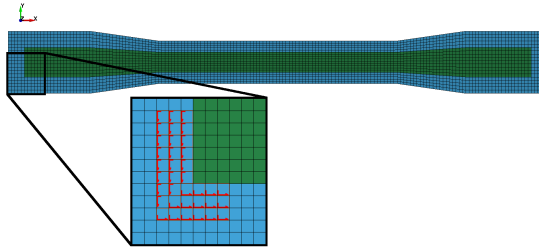


Figure 3: Configuration of the experimental tes

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Simulation-Driven Product Development for Additive Manufacturing

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Key Words: *Topology Optimization, Process Simulation, ANSYS*

Physics-based simulation software is key factor in enabling Simulation-Driven Product Development (SDPD) for many companies developing and manufacturing products today. The ability to virtually prototype and perform computer-based modeling of a product has allowed companies to drastically reduce design times and produce more reliable products [1]. As manufacturing moves from conventional techniques such as casting, forging, and machining to additive manufacturing (3D printing), the software tools must also evolve to support this new manufacturing paradigm.

Software features such as topology optimization are enabling efficient and radical designs that are inherent design freedoms afforded by additive manufacturing. Lattice-based design and cellular structures are also ways to capitalize on the nearly infinite complexity available via additive manufacturing. When the strut lengths are chosen appropriately, lattice structures produced by additive process are also self-supporting and less prone to failure due to excessive residual stresses. Hence, coupling cellular design with topological optimization using a physics-based approach can lead to novel and manufacturable designs while maintaining the required structural integrity [2]. Utilizing a homogenized-based approach leads to an efficient topology optimization algorithm that sizes the lattice members to meet the strength and stiffness requirements.

The output of topology and lattice optimization are typically faceted representations of the geometry, and require cleanup and smoothing to produce a usable surface representation. Additionally, PLM and other downstream needs often dictate that the representation be put back in a standard NURBS-based CAD format.

Additive manufacturing for metal structures uses a process where a metal powder or wire feedstock is melted by a laser beam or electron-beam building up a part layer by layer. The intense and repetitive heating and cooling lead to unwanted thermal distortions and residual stresses detrimental not only to the end use performance but to the build process itself, potentially leading to build failures. Simulating this process and predicting distortion and stresses is an important component in the additive manufacturing tool chain [3]. This has been an area of intense research the last few years [4] with many approaches of varying fidelity proposed.

While significant advances have been made in all these areas, in order to unleash the potential of additive manufacturing a streamlined and comprehensive software chain is required [5].

This talk will highlight the recent additions to the ANSYS Mechanical Enterprise product to not only support the simulation needs of additive manufacturing as mentioned above, but also harmonizing them into a seamless workflow. These two developments then facilitate Simulation-Driven Product Development for additive manufacturing.

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FE-based probabilistic analysis for fatigue assessment of AM parts

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Key Words: Additive Manufacturing, Defect Tolerant Qualification, Failure Probability Estimation

The unique strengths of the Additive Manufacturing (AM) process have motivated the spaceflight industry to take the lead in the incorporation of AM parts in structural applications. However, the qualification of AM structural parts needs a very costly and time consuming series of fatigue tests, on both samples and full-scale parts. Moreover, the benefits and degrees of freedom offered by the technology are counterbalanced by some important drawbacks, e.g., poor surface roughness, presence of manufacturing defects, material anisotropy. These variables influence the fatigue resistance, introducing some scatter in the material response, even inside the same batch of parts.

The aim of the research activity is to address this issue through a defect tolerant design applicable to every part manufactured. A literature review on different materials has demonstrated that manufacturing defects (mostly pores and lack-of-fusion) are one of the main causes of scatter. In addition to internal defects, a typical feature of AM is the presence of sub-surface clusters of pores close to down facing surfaces (see an example in Fig. 1a [1]). The influence of defect size can be assessed by means of the Kitagawa diagram, describing the size of the defects by the $\sqrt{\text{area}}$ parameter [1]. Even if the scatter in the fatigue limit can sensibly be reduced considering the defect size, some variability remains and should therefore be considered. The fatigue limit of a volume of material subjected to a given fatigue stress depends on the largest defect present in that volume. Micro X-ray computed tomography (CT) allows to investigate the defect population inside the material (see Fig. 1b) and peaks-over threshold maxima sampling can be used to simplify the description [2]. The application of statistics of extremes on the resulting population gives the distribution of the maximum defect in a reference volume [2, 3]. Knowing the stress applied on the component by means of a Finite Element (FE) analysis, every finite element can be regarded as a volume of material containing a given defect population. From the Kitagawa diagram, the failure probability of every element of the mesh is analytically calculated, as in Fig. 1c [3].

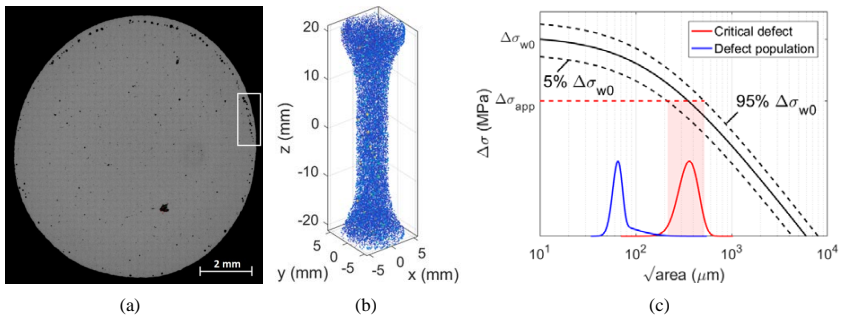


Fig. 1: (a) CT image showing internal defects and subsurface clustering [1]; (b) defects detected in a fatigue sample by CT; (c) determination of element reliability inside the Kitagawa diagram

The overall failure probability of a part having a complex geometry is assessed applying a Weakest-Link model on all the finite elements. The process does not follow the line of other well-known post-processors (e.g. P-FAT [4]) as the failure probability calculation derives from the distribution of the maximum defect in every element. The analytic formulation of the model guarantees a reduced computational effort with respect to repetitive Monte Carlo simulations (Fig. 2a), ensuring at the same time a mesh-insensitive result. Further implementations were introduced to account for the AM related issues, such as the intrinsic Kitagawa diagram variability detected in the experimental phase [5] and the influence of sub-surface clustering as a competing risk. The model has been implemented in a commercial FE software (Abaqus) by means of a Fortran subroutine. The practical application focused on an AlSi10Mg alloy produced by selective laser melting. The model has finally been validated on notched specimens (see an example in Fig. 2b).

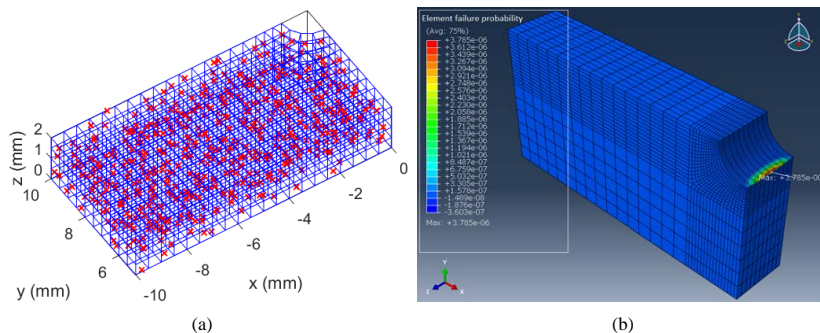


Fig. 1: (a) Monte Carlo simulation for analytical model verification; (b) failure probability calculation inside the FE environment for a notched specimen

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INNOVATIVE APPLICATIONS

Light absorption simulation and design of 3D printed cellular materials for solar application

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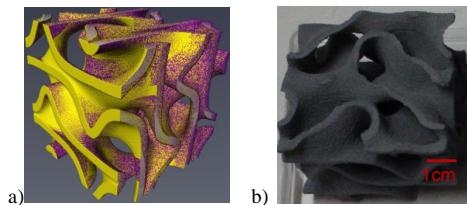
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Key Words: *Volumetric receiver, Additive manufacturing, Silicon Carbide*

Since the 1980s, concentrating solar power plants have been studied to obtain an alternative to the production of electricity by nuclear power plants. The general principle is to recover the energy of the solar rays to transform it into electrical energy. This transformation is carried out in three steps:

- 1) Concentration of solar rays to a volumetric receiver, using mirrors
- 2) Recovery and transmission of solar energy to a Heat Transfer Fluid (HTF)
- 3) Conversion of thermal energy into electrical energy by a power conversion system.

In this study, design optimization of the volumetric receiver is wanted. This device must absorb as much solar flux as possible and, transfer this absorbed energy to the HTF. The optimization of its 3D shape must allow to determine a structure satisfying this need and able to support high thermal stresses (operating temperatures $> 1000^{\circ}\text{C}$ and shocks due to weather conditions). Because of its physical properties, silicon carbide has been chosen to be the basic material of the receiver [1]. Nevertheless, complicated cellular structure designs are the result of our numerical approach. Additive manufacturing is the only way to produce these new structures.



The different steps of the numerical optimization are summarized in this abstract. First, a structure is generated by a home-made code which can generate voxelized structures from simple geometric shapes, grain growth, 2D image rotation, surface equations, and so on. Next, a home-made ray tracing code, based on Snell-Descartes laws, is used to simulate the localization of the sunlight absorption in the receiver (figure a). At this step, a first selection of structures of interest is made. This classification depends on the solar total absorption obtained and the spatial uniformity of the absorption along the

length of the receiver. This second parameter is a key to avoid high thermomechanical stresses [2]. Then, this absorption result is introduced as a boundary condition into a code that take into account the conducto-radiative heat transfer equations to calculate the temperature field induced in the solid structure. Then, the global heat exchange performance is determined with the help of the OpenLB software in which the fluid phase transport is computed [3].

To make the calculated structures we have used the binder projection additive manufacturing process. This technique makes it possible to produce pieces with complex SiC shapes (Figure b). However, the different post-treatments applied (pyrolysis, impregnation, CVI / CVD) make SiC of several natures. Thermal and mechanical characterizations are therefore carried out on small ligaments in order to deduce the properties of this material. These data will allow us, among other things, to get data's entry for the code of thermal calculation in the aim to predict as best as possible the behavior of the printed pieces.

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Function-driven design of a high temperature burner

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Key Words: *Function-driven design, Design for additive manufacturing, High temperature burner*

Design plays an important role in additive manufacturing. Besides influencing manufacturability and cost, the form of a part fundamentally determines its functional performance. Translating the required functions into a suitable form is thus key to obtain more energy efficient parts and systems. The following study presents an innovative design of a multi-media burner for high temperature applications. It integrates multiple flow structures into a monolithic geometry (see Fig. 1). In order to connect and supply the burner through pipes, the different fluid flows need to be distributed from circular pipes to larger, ring-shaped areas. Regarding the cooling of the structure, water is guided through the burner and returned to a central feeding system. For the combustion, the burner distributes various reactants. These may be swirled at the outlet to improve mixing rate and process conditions. The flows have to be distributed uniformly over a short part height while keeping pressure drop low.

The presented application is created through a function-driven design approach, which combines elements from creative thinking with modern tools from computer-aided engineering (CAE). In this study the fluid dynamic properties of the burner are of special interest, as they determine the performance of the combustion as well as the cooling efficiency of the structure. In order to design a single flow structure, its basic topology is first defined through a creativity-based approach and a set of design principles. The chosen design concept utilizes a widening skin surface that integrates multiple guiding blades. These blades are staggered such that the fluid is distributed with a branched flow pattern. A parametric CAD model is set up, which serves as a basis for a simulation-driven design optimization. As the guiding blades influence the flow distribution, their positioning is defined through a set of parameters such as pitch angle, height, and relative orientation. Results from a computational fluid dynamics (CFD) analysis are used to evaluate a certain parameter set. The distribution of the cooling water and the reactants are optimized with respect to maximized flow uniformity at the outlet and minimized pressure drop between inlet and outlet. Such a simulation-driven process allows a quick and automated exploration of a large design space. It is therefore well suited in conjunction with additive manufacturing, where the design space is much larger in comparison to conventional manufacturing. The burner demonstrates efficiency with regards to performance, cost, and lead time through function bundling, parts consolidation, improved flow distribution, and simplified assembly. In summary, a function-driven design approach in combination with a simulation-driven optimization is key to leverage the potential of additive manufacturing.

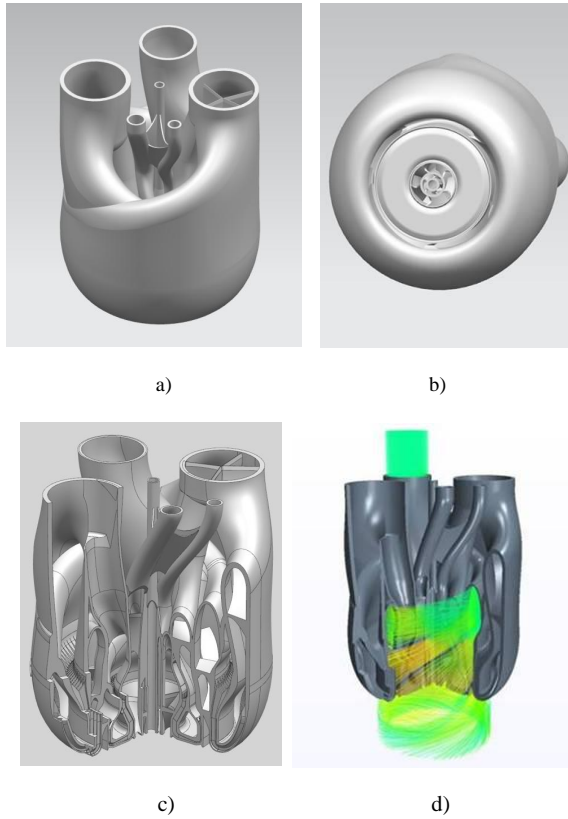


Fig. 1: a) High temperature burner designed for additive manufacturing;
b) Bottom view of burner design; c) Staggered cut of burner;
d) Visualization of streamlines for swirled distribution of reactant

Damage simulation for printed electronics: The effect of cohesive parameters on damage behavior

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Key Words: *printed electronics, cohesive zone model, damage parameter identification, multifunctional composites, smart materials*

Additive manufacturing allows the printing of structurally integrated electronics, especially sensors, to monitor the health state of a structure during operation. Depending on the constitutive behavior of the employed inks or pastes, these electronics can be applied by the use of inkjet or screen printing processes. Conductivity of the inks can be created by adding silver particles or carbon nanotubes. A particular application is to print the electronics on the outside or inside of carbon fiber reinforced plastics, i.e. a prevailing material in lightweight applications.

As structural components are usually designed with regard to their mechanical strength, integration of printed electronics may unfavorably weaken the structure. An understanding of the damage behavior of the printed electronics is required to predict overload and to save time, costs and effort during the design process. *Cohesive zone models* (CZM) have proven advantageous for modeling and simulation of damage behavior [2] and can also be applied to printed electronics [4]. While these models can help to give a detailed description of the damage behavior, their results can be sensitive to the employed parameters. Although there are some investigations on the effect of the model's underlying physical laws, i.e. the *traction-separation laws* (TSL) [1, 5], investigations on the effect of the cohesive parameters on the simulation result are much fewer [3].

In this work, an existing *finite element* (FE) simulation setup in ABAQUS is used to determine the cohesive parameters to match existing experimental data. The calculations are repeated with parameter configurations which are located around the optimal configuration. The different parameter configurations are evaluated and the effect of the parameters on the global simulation result is described.

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Modeling the 3D-printing of Electromagnetically Active Components

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Key Words: *electro-/magneto-rheological fluids, 3D-printing, Brownian Dynamics simulations*

3D-printing of multi-materials is used for manufacturing objects of complex geometry, with application to personalized (mainly medical) support equipment. Therefore this technique is researched in detail [1], also with respect to particle-filled materials. New advanced components can be made by applying external electric or magnetic fields, in order to manipulate the arrangement of the filler particles during the printing process. This kind of technology is already known and related to electro- and magneto-rheological fluids [3].

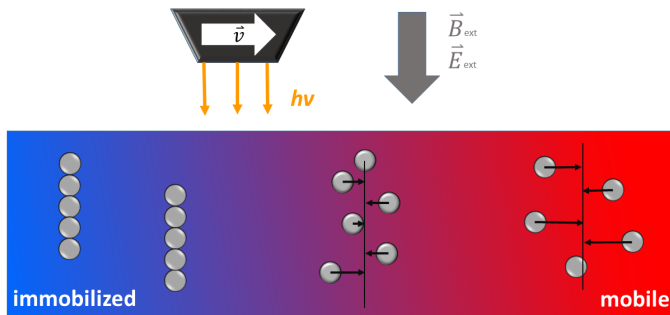


Figure 1: *Particles aligning under an external field.*

In his project, structure formation under externally imposed fields during 3D-printing is studied using Brownian Dynamics simulations, including the hydrodynamic-drag force, electric/magnetic interaction forces [2], and the Brownian (i.e. thermal) force. The model contains translational motion of the particles due to forces arising both from the external field and the interaction between the particles, as well as rotations coming from the different orientation of the dipole moments. The forces and torques used in this approach emerge as partial derivatives of the potential energy, both for spatially uniform and non-uniform fields, which is useful for proper model formulation. These interactions result in the formation of particle structures (e.g. chains, branched network), that turn the material anisotropic. The

modeling approach can also account for the fixation of the structure by solidification of the matrix material, which in reality is achieved by cross-linking the thermoset matrix by the exposure to light/UV, see Fig. 1.

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Numerical Modelling of Four Point Bending Test of 3D Printed Metallic Samples Equipped with the eSHM System

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Key Words: *eSHM system, capillary pressure, parameters study*

The present work concerns the utilization of the effective Structural Health Monitoring system, or eSHM system, for load monitoring purposes. The eSHM system was developed at the Department of Mechanical Engineering of the *Vrije Universiteit Brussel* (VUB), primarily for fatigue crack detection. It consists in integrating a capillary, whose dimensions are small compared to the structure, into the 3D printed structure that has to be monitored. The capillary is then over- or under-pressurized and connected to a pressure sensor, so that when a fatigue crack reaches the capillary, the sensor will detect respectively a pressure drop or pressure increase, thus revealing the presence of a crack. Besides its use for crack detection, the pressure variations in the capillary when the component is in service can also be processed in order to estimate the loading on the part and/or its strain state. In that context, and as a proof of the effectiveness of the system as a load monitoring system, Hinderdael *et al.* performed tensile testing of specimens equipped with the eSHM system, where the pressure variations in the capillary (the volume of the cavity changes due to its elongation and Poisson's effects, therefore leading to a modification of the pressure in the cavity) are used so as to obtain the loading state of the sample [1].

In this work, one focuses as well on usage monitoring (thus measuring the load and strain state of the structure), but this time in the scope of four points bending tests that were run by Strantza *et al.* [2]. In these tests, beam samples fitted with the eSHM were subject to loading/unloading cycles at 15Hz, where the amplitude of the load was increased per step until fatigue failure of the component occurred. During the loading/unloading cycles, due to the elastic deformation of the capillary through the cycles, one could notice that nearly sinusoidal pressure variations took place in the capillary (see figure 1), whose amplitude appeared to be function of the load step level.

The first objective of this research is to build a numerical model of the here above mentioned experiment that is able to capture the pressure variations in the capillary due to the application of the load cycles with a reasonable accuracy with respect to the experimental results (figure 2 shows the CAD geometry that will be used in the study) . This is done in the finite element environment *Abaqus CAE*, with the help of the fluid cavity feature, which links the volume changes of the cavity to the pressure variations inside of it. When a model is built that is validated by the experimental results, it will be used to derive a correlation between load level and amplitude of the sinusoidal pressure fluctuations in the capillary,

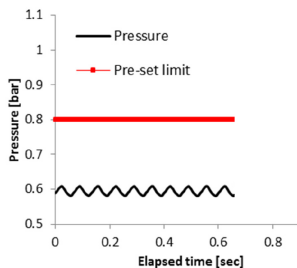


Figure 1: Pressure variation in the capillary during loading cycles. The pre-set limit concerns fatigue crack detection [2]

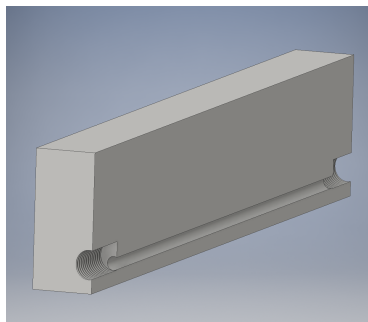


Figure 2: Cut view of the beam sample, showing the capillary and the location where the pressure sensors are connected

so as to obtain a measure of the sensitivity of the eSHM system when intended for load monitoring. Since Hinderdael *et al.* have shown the increased sensitivity of the system when the capillary is filled with water rather than with air [1], a second objective of this research will be to forecast by numerical simulations the amplitude of the sinusoidal pressure variations in case the capillary is filled with water. The quality of this forecast will then be assessed by comparison with results of experiments that will be done with water-filled capillaries. Finally, parameters such as position of the cavity in the sample, initial pressure in the cavity and shape of the cavity will be examined so as to obtain an insight on what the best system setup could be for efficient load monitoring.

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MATERIAL MODELLING

Numerical Investigation of the Influence of the Grain Structure on the Macroscopic Mechanical Properties of Additively Manufactured IN 718

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Key Words: *Crystal Plasticity, Gradient Plasticity, Grain Boundaries, Inconel 718*

Selective electron beam melting represents an additive manufacturing process where parts with complex geometries are built in a layer wise manner using metal powders. The powder is fused by the energy of an electron beam that is guided by electromagnetic fields allowing a very fast deflection and thus various scan strategies. Using these scan strategies it is possible to influence the resulting mesostructure in the material which may range from a columnar to an equiaxed grain structure.

For altered grain structures different macroscopic mechanical properties are expected. Long and similarly oriented grains cause highly anisotropic behaviour. In contrary, a uniform grain structure results in isotropic mechanical behaviour. In summary the different orientations and the effects of grain size and boundaries strongly influence the macroscopic mechanical properties.

In this contribution the macroscopic material behaviour is simulated by means of mesoscopic Finite Element simulations. Like in [2] a Voronoi tessellation based method is used to model the grain structure of columnar grained Inconel 718. On the mesoscale the thermo-mechanical behaviour is modelled using the thermal gradient-crystal-plasticity model from [3], accounting for relative misorientations on the grain boundaries with the formulation in [1]. Computational homogenization is used to identify elastic and plastic temperature-dependent macroscopic mechanical parameters such as the anisotropic Young's moduli or the yield surface. Numerical results are validated with experimental data.

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Phase-field model for microstructural evolution during metallic glass formation

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Key Words: *Phase-field model, Glass formation, Amorphous metal, Bulk metallic glass, Nucleation*

Introduction

Bulk metallic glasses (BMGs) is a promising novel class of materials with remarkable mechanical and magnetic properties in comparison to conventional metallic materials. Attributes such as high strength, high resilience, high corrosion resistance and excellent soft magnetic properties makes them suitable for a wide range of engineering applications [6]. Synthesizing BMGs can be a cumbersome task that typically requires high cooling rates, which implies limitations on component size and complexity when produced with conventional casting [6]. The layer by layer approach utilized in additive manufacturing (AM) enables the possibility to maintain high cooling rates and serves as a promising alternative to casting with the capability to produce BMG components without geometric limitations [4]. However, components manufactured by AM undergo severe heating and cooling during processing, which affects the final properties of the component. The processing steps have a strong influence on the microstructural evolution of the material and the processing parameters needs to be tuned accordingly. Understanding and being able to predict the microstructural evolution during glass formation is therefore of fundamental importance in order to successfully produce BMG components through additive manufacturing. In the present work, a computational modeling framework for glass formation is presented. It is based on the phase-field description and has been developed to capture the thermodynamic and kinetic interplay that causes the phenomena of glass formation.

Modeling approach

Bulk metallic glasses are commonly synthesized through rapid cooling of an alloy melt in order to achieve substantial undercooling of its liquid state. The rapid cooling causes a reduction in the atomic mobility of the melt, implying reduced kinetics that limits the long range atomic rearrangements required for crystallization. In other words, crystallization is bypassed, causing the atoms to "freeze" in an amorphous atomic configuration at a temperature referred as the glass transition temperature [6]. To simulate this behaviour, a phase-field model has been developed to predict the process of crystalline

nucleation from an undercooled liquid melt. The model parameters are adapted to experimental data for the BMG alloy AMZ4 ($\text{Zr}_{59.3}\text{Cu}_{28.8}\text{Al}_{10.4}\text{Nb}_{1.5}$) [3]. The evolution equation is implemented and solved by utilizing the finite volume PDE solver FiPy [2] with a fully implicit backward Euler time-stepping scheme.

Phase-field model

The phase-field method uses a scalar order parameter $\phi(\mathbf{x}, t)$ to describe the inhomogeneous distribution of the phases present in the material [5]. The order parameter is continuous in time t and space \mathbf{x} and has the value $\phi = 0$ or $\phi = 1$ in each of the two bulk phases. The transition between the phases is described by the symmetric polynomial $g(\phi)$ and the assymetric polynomial $p(\phi)$ and are used to define the free energy density of the bulk phases as

$$f(\phi, T) = Wg(\phi) - \frac{\Delta G^{L-S}(T)}{V_m}p(\phi) \quad (1)$$

where W is the energy activation barrier, $\Delta G^{L-S}(T)$ is the difference in Gibbs free energy separating the two states and V_m is the molar volume. By substituting Eq. (1) into Allen-Cahn's equation [5], the evolution equation for $\phi(\mathbf{x}, t)$ becomes

$$\frac{\partial \phi}{\partial t} = M_\phi(T) \left[\epsilon_\phi^2 \nabla^2 \phi - W \frac{dg(\phi)}{d\phi} + \frac{\Delta G^{L-S}(T)}{V_m} \frac{dp(\phi)}{d\phi} \right] + \eta(\mathbf{x}, t) \quad (2)$$

where ϵ_ϕ is the gradient energy coefficient and $M_\phi(T)$ is the mobility of the interface, assumed to be dependent on temperature as a representation of the kinetic slowdown observed during glass formation. The last term in Eq. (2) is a statistical thermal noise [1], chosen to satisfy $\langle \eta(\mathbf{x}, t) \rangle = 0$ and $\langle \eta(\mathbf{x}, t) \eta(\mathbf{x}', t') \rangle = 2M_\phi k_B T \delta(\mathbf{x} - \mathbf{x}') \delta(t - t')$, where the primes denote a position and time different from the unprimed variables and k_B is the Boltzmann constant.

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Modeling of Microstructure evolution in Additive Manufacturing processes of Ti6Al4V

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Key Words: *Additive Manufacturing, Metal deposition, Process simulation, Thermal Modeling, Microstructure Modeling, Ti6Al4V*

During iterative metal depositions, alloys experience thermal cycles characterized by an unusual range of cooling and heating conditions, if compared with traditional forming processes. The complex temperature evolution influences directly the kinetics of microstructure formations during solidification and solid state transformation. This leads to unique microstructural and mechanical properties that are distinct from cast or wrought parts obtained from identical alloys [1].

Accurate data of temperature evolution during the process are strictly needed in order to provide the thermal inputs for the modeling of microstructure formation in each point of the part. At CIMNE, several activities of thermal simulations of AM processes have been successfully carried out using COMET, a self-developed Finite Element (FE)-based framework for the solution of engineering problems [2, 3]. In these cases, a thermal solution that includes phase-change phenomena was adopted. The welding path was modeled by means of an ad-hoc activation methodology that switched on the elements according to the scanning sequence. The aim of this work is to enhance the tools of AM process simulation available at CIMNE, focusing on the implementation of models for microstructure evolution of Ti6Al4V.

A review of the state-of-the-art has been carried out in order to define which microstructural transformations take place during AM processes of a Ti6Al4V alloy and which are the most suitable models for the description of each transformation. During a general cooling, three different main transformations can take place: solidification of β phase from liquid, $\beta \rightarrow \alpha + \beta$ solid state transformation and a_m martensite formation. Below liquidus temperature, β phase (BCC crystal structure) starts to form. Depending on the cooling conditions, β grains can show equiaxed or columnar morphologies [4]. Following the cooling path, when the β -transus temperature (around 995° C) is reached, α phase (HCP crystal structure) starts to form from the previous β phase. Generally, slow cooling rates lead to Widmanstätten structures, composed by α lamellae, with small amount of intra-lamellar retained β . The $\beta \rightarrow \alpha + \beta$ diffusion-controlled transformation can be modeled by means of a Johnson-Mehl-Avrami-Kolgorov (JMAK) equation [5] using the principle of the additivity rule [6]. JMAK equations are defined by temperature-dependent parameters that can be inversely extracted from literature data of Temperature-Time-Transformation (TTT) curves. α lamellae are usually aligned to form colonies and the α lath thickness, inversely proportional to cooling rate, can be modeled by an empirical Arrhenius equation. In case of faster cooling rates, martensite a_m (a non-equilibrium phase with acicular shape) can form from the residual β . This transformation is considered diffusionless and can be modeled using the Koistinen-Marburger law, an empirical relationship dependent from the undercooling below the martensite start temperature T_{ms} [7]. In the case of re-heating, three different main transformations can occur: decomposition of a_m to $\alpha + \beta$, dissolution of α to β and remelting of β . Gil Mur [8] proposed to model the $a_m \rightarrow \alpha + \beta$ transformation with JMAK equations using experimental parameters extracted from martensitic samples reheating

data. Considering the high heating rates of AM processes, $\alpha \rightarrow \beta$ transformation can be approximated (as the re-melting of β) as an instantaneous transformation which follows the equilibrium phase diagram [9]. However, other approaches to β recovery have been adopted in literature, such as the additivity rule with JMAK equations or the model proposed by Kelly [10], a time dependent parabolic law multiplied by a calibrated function of temperature.

The previous exposed models have been implemented in a routine, similar to the one presented in ref [11], allowing to switch from a transformation to another and to consider previous incomplete transformations. The validation of the microstructural models has been performed comparing the simulations results with data available in the literature. For some specific transformations, the outcome obtained using different models are discussed. Considerations about the sensitivity of the overall model to the variation of material parameters are also presented. Due to the high dependence from experimental parameters, future activities of material characterization could sensibly improve the accuracy of these microstructural models.

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Computational analysis of grain structure evolution during selective laser melting

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Key Words: *Additive Manufacturing, Selective Laser Melting, Heat Transfer, Evolution of Grain Structure*

Development of numerical models to describe crystallization processes taken place during metal additive manufacturing allow one to optimize the process parameters and improve the properties of additive manufactured parts on the one hand as well as deepen the understanding of the microstructural evolution as a whole. We developed two- and three-dimensional grain growth models to describe the evolution of internal structure in a representative volume of additive manufactured material.

The main objective in the development of the grain growth model was to achieve a sufficient computational volume to analyze the effects of the heat source parameters and scanning strategy on the evolution of grain structure and, in the long run, on the mechanical properties of additive manufactured material. As part of the model, a heat source is described explicitly with the use of Goldak double ellipsoid model [2]. Cellular automata approach put forward by Rappaz and Gandin [3] describes grain growth. To minimize the mesh-induced anisotropy, we adopted a decentred octahedron algorithm [3]. The simulation results showed good qualitative agreement with experiment.

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Multiphysics Modeling of VAT Photopolymerization for Additive Manufacturing of Ceramics

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Key Words: *Coupled multi-physics, heterogeneous material, micro-scale modeling, ceramics, VAT photopolymerization*

Additive manufacturing (AM) of ceramics is considered a potential breakthrough technique considering the added design freedom that can not be achieved using conventional production techniques. The current state-of-the-art facilitates accurate fabrication of complex, small and most importantly, thin walled structures, such as micro reactors [4]. However, the production of large-scale technical ceramics with thick walled structures remains challenging.

The focus in this contribution lies on the indirect process of fabricating a ceramic (near) net shaped product through a so-called ‘green’ intermediate phase using VAT photopolymerization, i.e. stereolithography. Starting from a three-dimensional computer model, a repetitive process of depositing a layer of ‘slurry’ consisting of monomer, photoinitiator and ceramic particles, and selective illumination by UV light ultimately results in the complete green phase product. In a subsequent heating step the polymer, i.e. the solidified or cured monomer, is debonded and the ceramic particles are sintered together into an ideally fully dense final product [2]. This process is illustrated in Figure 1. Although the latter two process steps, i.e. the green part post processing steps, are crucial in developing the intended ceramic product, the focus lies on the printing process itself.

In order to obtain a better understanding of relevant phenomena and key parameters in the printing process a numerical approach is used. From a modeling point of view, the entire process is of a highly multi-physical nature. The deposition of the viscous fluid layer with dispersed particles requires a rheological model. The subsequent illumination through the layer of slurry is a physics problem, even more eminent due to the light scattering induced by the ceramic particles [2]. The consequential polymer

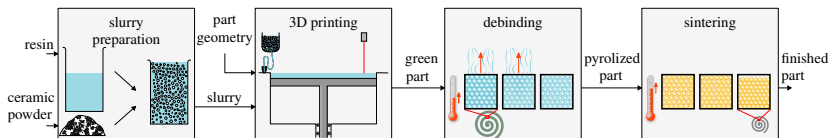


Figure 1: Abstract overview of the ceramic production process.

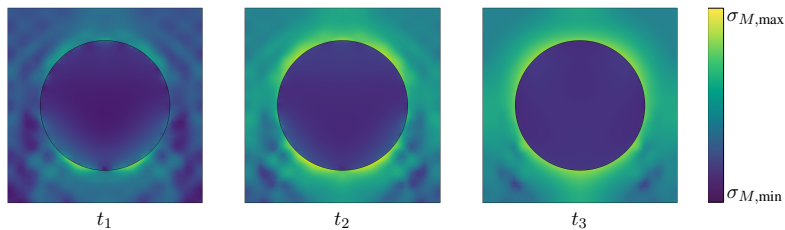


Figure 2: Illustration of the inhomogeneous evolution of the Von Mises stress during polymerization as a result from light scattering by a ceramic spherical inclusion.

curing process poses a chemical one, in which the exothermic reaction generates heat [1]. Finally, a degree of conversion dependence is required in a mechanical model to relate to e.g. viscosity, chemical shrinkage, thermal expansion and internal stress.

The proposed finite element model assumes a quasi-static situation, i.e. ignoring the layer deposition process. Due to the small difference between the particle dimensions and the wavelength of the light an electromagnetic wave description is required for the light propagation. A clear separation in time-scales is introduced by solving the response to the monochromatic laser light in the frequency domain. It should be noted that this electromagnetic wave assumption also allows for reproducing the typical Beer-Lambert like attenuation of light in an unfilled system [3] or photobleaching of the initiator. The local light intensity is then coupled to cure kinetics, which in turn induce a time-dependent increase in temperature, primarily due to reaction heat, and an evolution of mechanical properties. From here the influence of different model parameters on effects ranging from light propagation, degree-of-cure profiles to resulting stresses can be examined. An example of the latter is depicted in Figure 2, where the stress evolution during polymerization around a single ceramic particle is illustrated. In this particular case the $1\text{ }\mu\text{m}$ particle is subjected to UV light. The effect of particle arrangement on the degree of conversion and internal stress is investigated using this coupled modeling approach.

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Modeling of melting, solidification, and microstructure evolution in laser powder bed fusion process

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Key Words: *Phase field modeling, Rapid solidification, Laser Additive Manufacturing, Microstructure Evolution*

Additive manufacturing (AM) processes are receiving widespread attention due to the ability to create or repair precision engineering components without use of any die or mold. Currently, the approach to obtain a specific user defined epitaxial microstructure is a challenging and expensive iterative process. Modeling and validation of solidification microstructure can be leveraged to reduce iteration cost in obtaining a desired microstructure. We developed the combined approach in microstructure prediction during laser powder bed fusion (LPBF) process. Numerical Volume-of-fluid based method incorporating Marangoni convection can accurately predict the resultant melt pool geometry and temperature distribution which can serve as an input in prediction of microstructure evolution in solidifying mushy region. Hence, in the present study, computational fluid dynamics (CFD) analysis is used to predict melt pool characteristics and phase field modeling is employed to simulate microstructure evolution in the as-deposited state for LPBF process. The phase field framework is also modified to incorporate the convection term in scan direction, and it is coupled with the concentration equation to predict segregation of secondary elements and microstructural transition. Different features of LPBF microstructure such as segregation of secondary elements, rapid solidification effect, dendrite sizes, dendritic orientation, dendritic morphology, and surface roughness are investigated and validated through comparison with experimental results. Phase-field Model suggests strong dependency of dendrite orientation on surface roughness and scan speed, and suggests potential of columnar flip or oriented-to-misoriented transition at higher scan speed. Segregation of the secondary elements is found to be the dominant factor in resultant dendrite width in the range of 1 to 3 μm . Furthermore, the developed method is extended to predict the change in orientation of dendrites as new layers are built atop previous layers. Undergoing work is focused to include effects of non-linearity in phase diagram by coupling thermodynamic database with concentration equation for model ternary alloy, as well as extension of the current models to predict grain structure in 3D using HPC clusters with objective of predicting residual stress and fatigue life for as-deposited AM components.

Melting and Solidification for Powder Based Additive Manufacturing Using Optimal Transportation Meshfree Method

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Key Words: *Selective Laser Melting, Phase Change, Meshless Method*

Selective Laser Melting (SLM) is an additive manufacturing (AM) process, where a powder bed is partially melted. Layer by layer, complex three dimensional geometries including overhangs can be produced, because non-melted powder acts as support structure.

Up to date the multiple interacting physical phenomena are not yet fully understood. This is why the material and process development mainly relies on experimental studies that are time and cost intensive. Novel simulation tools such as meshless methods offer the potential to gain a deeper understanding of the process - structure - property interaction. This can help to find optimal process parameters and to individualize AM manufactured parts by locally altering material properties.

Using conventional FEM methods, extremely large deformations of the mesh lead to ill-shaped elements and per consequence to degenerate computations. Meshfree methods eliminate the mesh dependency by employing a more flexible formulation to relate a point of integration to its neighboring nodal points. This requires flexible shape functions that depend on the nodal positions only [1].

The Optimal Transportation Meshfree (OTM) Method is a meshless method based on the weak formulation of the differential equations and can be downscaled to the Finite Element Method. It accounts for a broad variety of materials ranging from solids to fluids [2] including thermo-mechanical behavior.

This flexibility makes the OTM an optimal tool to simulate the melting of powder particles and the motion of the melt flow. An approach to account for the phase transition and the fusion of particles using OTM will be presented. Furthermore, the behavior of the metal during solidification is assessed. Releasing the induced residual stresses can yield undesired deformations and destroy AM parts.

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Molecular Dynamics Simulations of Waterborne Biodegradable Polyurethane Hydrogel for 3D Printing

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Key Words: *waterborne biodegradable polyurethane, molecular dynamics, 3D printing, biomaterials, hydrogel*

Biodegradable hydrogels have become popular materials for many biological applications in the past years. They not only exhibit similar mechanical properties as natural soft tissues but also have the ability to be degraded in an aqueous environment after their useful lifetime. Recently, a novel waterborne biodegradable polyurethane (WDPU) has been synthesized and shown to have great potential in biomedical applications. It is synthesized by a green water-based process, and has great biocompatibility, biodegradability, and mechanical properties. Furthermore, it has been used as a 3D printing ink recently to enable the fabrication of biocompatible scaffolds. The integration of biodegradable hydrogel and 3D printing technology has open great opportunities for the design of smart biocompatible scaffolds for many applications due to the ability to access complex internal structures. However, the molecular mechanisms of the self-assembly process of waterborne PUs and the relationship between the chemical compositions of the polymer segments and the material properties of the biodegradable hydrogels are still not clear.

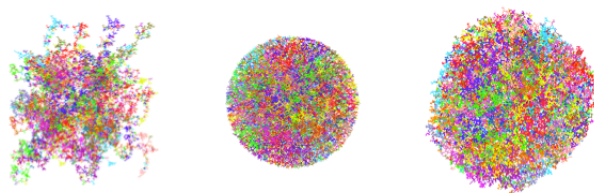


Figure 1. Molecular structure of amorphous WDPU and WDPU nanoparticle.

In this study, we aim to explore the fundamental mechanisms of the WDPU through a full atomistic simulation approach. We use molecular simulations to study the molecular structures of the WDPU containing different soft segments including PCL and PLA. Amorphous unit cells for different WDPU are constructed to study the temperature dependences on the mechanical properties. Furthermore, the WDPU nanoparticles are constructed to study the self-assembly process of the WDPU hydrogel (Figure 1). The end-to-end distances of polymer chains, radius of gyration, and solvent accessible surface area of WDPU nanoparticles are analyzed to investigate the self-assembly behavior, transition temperature, and mechanical properties of WDPU nanoparticles. We find that the material properties of the biodegradable hydrogel can be designed by tuning the molecular weights and the chemical compositions of the polymer segments in the WDPU. Our results provide fundamental insights into

the self-assembly process of WDPU nanoparticles and help enabling the design of material properties of biocompatible hydrogel for future 3D printing applications.

Simple modeling of biological composites, kirigami, and viscoelastic crack propagation

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Key Words: *nacre, spider webs, scaling laws, coarse-grained model, kirigami, crack propagation*

In this talk, we use simple models to provide a clear understanding of mechanical properties of different materials. We discuss biological composites, kirigami (sheet of paper with many cuts), and crack propagation in viscoelastic materials.

In certain biological composites such as nacre and spider webs, the combination of soft and hard elements seems indispensable for achieving high strength and toughness. In this talk, we discuss the mechanical superiority of such soft-hard biological composites. As a result, we provide an intuitive understanding of how their remarkable structures contribute to enhancing their fracture resistance in the presence of cracks, and how such structures are physically optimized in terms of mechanical properties [1-3].

Kirigami is a highly stretchable sheet material and has been received much attention especially because of its potential for various engineering applications such as graphene kirigami and stretchable batteries. In this talk, we show that the high stretchability emerges from a transition from in-plane to out-of-plane deformation, providing scaling laws that describe experiment well [4].

It is known that the velocity of crack propagation in elastomers exhibits a significant jump as the applied load is increased, which could trigger catastrophic failure in automobile tires. Physical understanding of this velocity jump is important from fundamental and industrial points of view. In this talk, we present an exactly solvable model for the phenomena to provide a clear physical understanding of the velocity jump [5].

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Finite element simulation of Ti-6Al-4V direct metal deposition

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Key Words : *Direct Metal Deposition (DMD), Titanium Alloy, Phase transformation, Finite element*

The numerical modelling of additive manufacturing processes can help to predict the residual stresses and permanent strains in mechanical parts at the end of fabrication. The initial CAO and the machine parameters can then be optimized "a priori" in order to minimize these residual stresses and get the expected final geometry. An accurate prediction of the micro-structure generated by additive manufacturing process is also useful in order to forecast the mechanical properties of the manufactured material. It is particularly important in the case of Ti-6Al-4V alloy for which the final micro-structure is highly dependent on the process parameters namely the laser power, the laser speed or the powder mass flow [3]. The manufactured part can be at the end composed of the phase α which is hexagonal close packed (HCP), the phase β which is body centred cubic (BCC), the martensitic phase α' , or a homogeneous or heterogeneous mixture of two or three of these phases.

The prediction of the metallurgical phases at the end of the fabrication requires an accurate knowledge of the thermal path experienced by each point of the manufactured part. For that purpose, a thermal finite element model of direct metal deposition has been developed by A.Longuet [1] and G.Marion [4] and validated using some comparisons with experimental measures. The temperature fields obtained from these simulations are then used as an input of a metallurgical model in order to predict the evolution of phases all along manufacturing process. The final metallurgical state obtained for four different sets of process parameters are compared with the corresponding experimental measures in order to validate the modelling approach.

The thermal and metallurgical fields obtained from both present model are then used as inputs of a mechanical finite element simulation of the direct metal deposition process. A mean field mechanical

model is build based on the mechanical behaviour of each phase [2], and used in the finite element mechanical simulation in order to evaluate the residual stresses and strains at the end of manufacturing. The deflection of the manufacturing substrate obtained from the simulation is found to be in good agreement with the corresponding experimental measures.

This three step (thermal - metallurgical - mechanical) finite element analysis can be used to simulate the manufacturing by direct metal deposition of simple industrial parts, and can help to optimize the process parameters, or the initial geometry or the part, in order to minimize the residual stresses and strains.

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From 3D images to 3D printed optimized materials for high temperature thermal insulation

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Key Words: Stereolithography, ceramic, thermal insulation

Since a few years, a small revolution is happening in material science through the development of experimental techniques leading to get the 3D representation of significant volume of material at a representative scale (TEM, FIB/SEM, X-Ray micro-tomography). Thus, using more and more powerful image processing techniques, new microstructural analysis approaches arise to study materials from nanometers to millimeters scales. Moreover, recent computer abilities (especially high performance computing solutions) allow achieving numerical experiences to estimate some physical properties of materials through the use of their 3D numerical description. Nevertheless, these computations can only be done if the properties of each component of the material are known at the appropriate scale. Beyond the estimation of properties of a given material, these simulations enable the development of optimized materials. In fact, the 3D microstructure can be numerically transformed or can be entirely designed by computer. Also, in numerical simulations, the base component properties can be easily changed. Then, according to thermal and/or mechanical specifications, an optimized material can be designed by changing either the microstructure and/or the base component properties. The Figure 1 shows different steps of the process; from 3D numerical design to real test through numerical simulations.

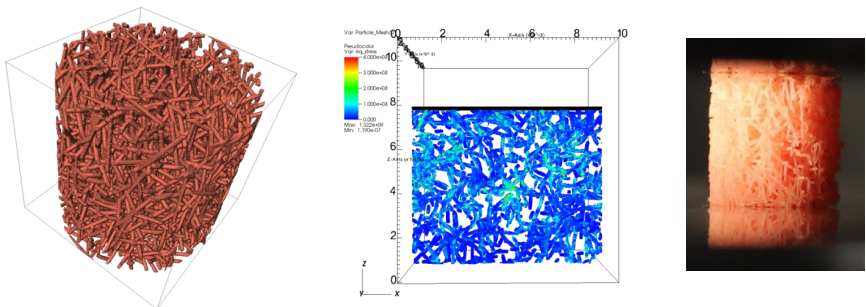


Figure 1: 3D voxel representation of a fibrous numerically created sample (left). Extraction of constraint field during a dynamic compression simulation (center). Same sample (made by additive manufacturing) before a quasi-static compression test (right).

In this study, the reasoning described above is applied to develop new thermal insulating materials. Super-insulating materials (material with better thermal properties than air) are usually mechanically very fragile. To improve mechanical performances of such media without degrading its thermal properties, the addition of solid skeleton, made by additive manufacturing, is studied. Then, we present the simulation leading to the best compromise between thermal and mechanical behaviors. All the simulations are fed by local characterizations. Thus, the influences of the printing parameters are taken into account in the calculations.

Another specificity of this work is the need for this material to work at high temperatures ($>1000\text{ }^{\circ}\text{C}$). Then, the 3D structures are made by stereolithography using inorganic loaded resins. Finally, comparisons between simulations and experiences are made for thermal properties as well as mechanical ones.

Effect of materials properties in 3D product geometry during stereolithography

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Key Words: *SLA, materials modeling, warpage*

The 3D printing of parts using stereolithography (SLA) consists of making use of a photocurable liquid resin in combination with a layer-by-layer manufacturing process in order to materialize the digital design of an object [1]. SLA technology has several features, of which it is worth mentioning the potential for printing complex shapes with high resolution. Additionally the type of resins utilized in SLA is made of a mixture of different components [2]. In a simple recipe we found at least three components namely the reacting monomer, photoinitiator and dye. It is clear that the final properties of the printed object will be dependent upon the concentration of the components in this recipe, but also on the process conditions. In the modeling of SLA the link between the process and materials settings is often overlooked. Typical questions such as: does it help in reducing internal stresses to have a heat sink or a heat insulator as mounting plate? or, what is the relative change in the final warpage of an object when the concentration of the dye changes? are often left unanswered. In this work we present a simulation framework that combines the SLA printing process together with a material model of the resin including its kinetic, thermal and mechanical behavior. By using such framework we can vary either the material or process parameters in order to estimate what their influences would be in the final quality of a printed object. The object in question is a simply-supported square plate formed by the addition of subsequent number of layers. We first look into the effects of the inhomogeneity and the geometrical-nonlinearity on the resulting stresses and strains in the printed object. Secondly, we pay attention to the final warpage obtained along the object when resin properties, such as the dye concentration or the reaction rate for radical formation, are changed and how it depends upon the number of layers printed. Currently we are working towards validation of the framework utilizing experimental data on printed test samples. We also will discuss how such validation could be carried out using the information gathered commonly for the calibration of the optimal printing and material parameters.

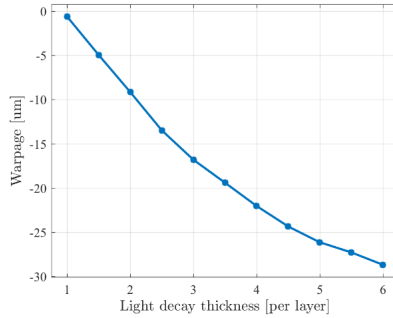


Figure 1 The final warpage of 3D printed plates with different concentrations of the dye, which influences the light decay thickness.

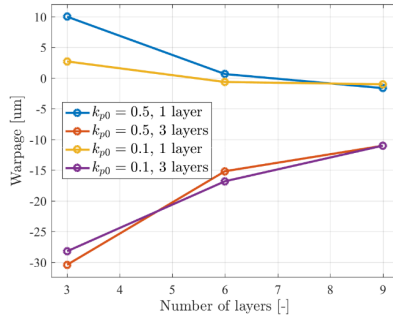


Figure 2 The resulting warpage of 3D printed plates when material is tuned to different reaction rates.

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Numerical simulation of laser shock processing effects on residual stresses of Multi-layer butt-welded stainless steel joints

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Key Words: *Butt-welded Joints, Weld Residual Stress, Laser Shock Peening, Numerical Simulation*

Abstract: To investigate the residual stresses variation in Cr13-type low carbon martensitic stainless steel multi-layer butt-welded joints subject to laser shock processing (LSP), LSP simulation is performed with the weld residual stress as the initial status by ABAQUS software. Influences of shock parameters such as laser pulse energy, spot sizes, pulse width, multiple shots and overlapping rate on the residual stress are mainly studied for the purpose of optimizing these laser shock parameters by comparing the residual stress fields before and after LSP processing. The results show that LSP has made the residual stress change from tensile residual stress to high-level compressive residual stress on the stainless steel welded joint surface. Residual stress distributions could be significantly improved by optimizing the processing parameters. The ideal residual stress field without “residual stress hole” could be obtained under the condition of 36 J of laser pulse energy, 2.5 mm of spot radius, 30 ns of pulse width, 3 ~ 4 of shock numbers and 75% of overlapping rate.

Introduction: Cr13-type low carbon martensitic stainless steels are an economical option for the demand of superior mechanical properties and high corrosion resistance. However, higher residual thermal stresses often occur near the weldment due to uneven heating and subsequent rapid cooling in welding process, while such weld residual stresses especially tensile residual stresses may cause crack initiation, accelerate crack propagation, and even finally lead to the fracture of welded structure and disastrous consequences under the combined action of service load and environment [1]. Therefore, it is of great importance to control the magnitude and distribution of the residual stress by LSP technology [2] for improving the resistance to stress corrosion cracking and the service life of these stainless steel welded structure. At present, little effort has been devoted to modeling the role of LSP in performance improvements of stainless steel welded joints after LSP. So, it is necessary to investigate the changes of the residual stress fields before and after LSP through using finite element method.

Results and Discussion: Fig.1(a) shows the welding geometrical model and the sequence of the weld passes, while Fig.1(b) shows the mesh of the 3D finite element model in which the heat source center is moving along the Z direction in welding line. The comparison of weld residual stresses computed in the present paper and measured by Thibault et. al. [3] has been conducted as shown in Fig.2. It is noticed that our simulated results are basically in good agreement with Thibault's results. Fig.3(a) shows the contours of equivalent stress induced by different overlapping rates. As shown in Fig.3(a), for the 75% overlap case, the center of the laser spot is lapped just on the center of the former spot

radius and the maximum compressive residual stress occurs on the center of the spot radius, which just counteracts the influence of the "stress holes". Therefore, the residual stress distribution is more uniform. Fig.3(b) indicates the transverse residual stresses distribution under multiple LSP shots and $\varphi=75\%$ overlapping rate. In the cases of the same laser overlap rate (75%), the average compressive residual stress and depth of compressive stress layer are increased with increasing LSP shots, but their values tend to be constant after 4 laser shots.

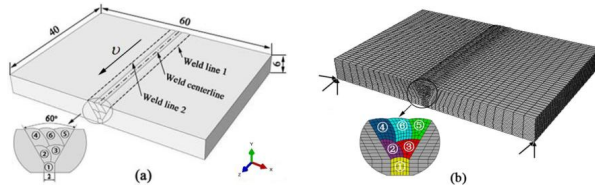


Fig. 1. Analysis model: (a) Geometry model, and (b) 3D finite element model and weld pass locations of the butt-welded joint (all dimensions in "mm").

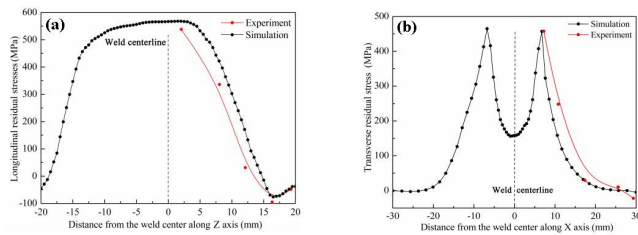


Fig. 2. The comparison of weld residual stresses: (a) longitudinal and (b) transverse residual stresses computed in the present paper and measured by Thibault [3]

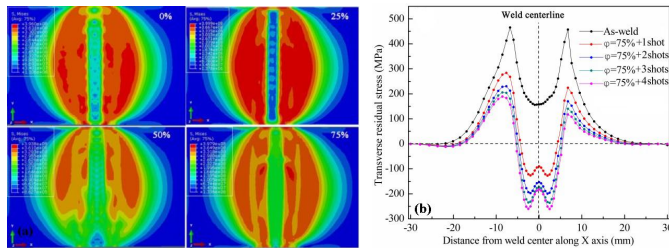


Fig. 3. (a) The contours of equivalent stress under different overlapping rates and (b) transverse stress under multiple LSP shots with the overlapping rate of 75%

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Efficient non-deterministic analysis of PA-12 components, produced via Laser Sintering

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Key Words: *Laser Sintering, Non-deterministic analysis, Uncertainty Quantification*

Additive Manufacturing (AM) techniques are becoming increasingly popular for the production of functional components. In the context of producing plastic parts for end-use applications, Laser Sintering of PA-12 is deemed to be one of the most promising AM processes, as it offers a good compromise between dimensional accuracy and mechanical performance [1]. However, despite the maturity and wide application of the Laser Sintering process, produced parts still present a large variability in their elastostatic properties. This variability is caused by complex interactions between both the process parameters (e.g., scan speed, path orientation), process state variables during the process (e.g., local temperature), material parameters (e.g., melt viscosity and -enthalpy) and the process planning prior to production (e.g., placement of parts in the envelope). This variability manifests itself both in low-level material properties such as porosity [2] and crystallinity [7], leading also to a non-trivial amount of variability in high-level properties such as Young's modulus and yield strength, sometimes up to 7% of the nominal value in a single batch [4]. Moreover, recent work by the authors has also indicated that intra-variability is present on Young's modulus of PA-12 parts produced via Laser Sintering, caused by differences in scanned cross-sectional area between subsequent layers [4]. Therefore, in order to obtain a reliable and robustly designed functional component the inherent variability that is present in the elastostatic properties of PA-12, produced via Laser Sintering, has to be taken into account already during the design process.

This paper first therefore presents an overview of the variability in the elastostatic properties of Laser Sintered PA-12 parts based on mechanical tests, performed on a test population with a statistically relevant size. This test population includes the effects of building orientation and location in the build platform, two parameters that have been shown to influence the elastostatic properties to a large extent [5]. Based on this dataset, two non-deterministic constitutive models are constructed: a homogeneous probabilistic isotropic model and a heterogeneous interval field isotropic model (see e.g., [3] or [8] for an explanation of the concept of interval fields). As such, both probabilistic and possibilistic techniques are considered for the representation of the non-determinism that is present in the elastostatic properties of PA12 parts, produced via Laser Sintering. These non-deterministic material models are subsequently used to model the non-deterministic elastostatic response a well-defined benchmark specimen (which is shown in figure 1), and the results of both models are critically compared in terms of computational cost and predicted variability. Hereto, a Finite Element model is constructed to simulate a predefined

loading situation of the benchmark specimen, and the non-determinism in the constitutive model is propagated through this model. Specifically, the probabilistic model response (in terms of probability density functions of the stress and strain responses) is approximated using Monte Carlo sampling, whereas the interval field model is solved for the respective uncertain realisation sets using the Transformation Method [6]. Finally, also a set of 12 replica of this benchmark specimen are produced using Laser Sintering in PA-12, and the mechanical response is measured using Digital Image Correlation (DIC) in order to assess the real-world accuracy of both non-deterministic material models. Figure 1 shows the measured strain fields in this benchmark sample at a load of 1500N.

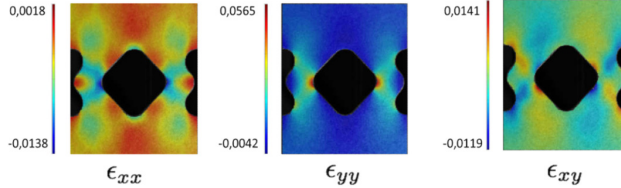


Figure 1: Longitudinal (ϵ_{yy}), transversal (ϵ_{xx}) and shear (ϵ_{xy}) strain fields in the loaded benchmark component (taken from previous work of the authors in [4]).

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Towards the modelling and simulation of additive manufacturing via phase transformation models

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Key Words: *Constitutive modelling, process simulation, phase transformations*

Additive manufacturing exhibits a great potential for innovative and efficient industrial applications. The effect of the associated process parameters on the properties of the final workpiece are, however, still rather vague, in particular for laser powder cladding. Thus, material and structural designs in order to obtain desired or, in other words, optimised properties are rather based on empirical knowledge. This motivates the need for sophisticated material and process models in the context of additive manufacturing processes.

The characteristics of processes such as the aforementioned laser cladding or selective laser melting render the computer-based modelling and simulation challenging. Not only that the constitutive behaviour of the respective material in its powder, molten and re-solidified form has to be captured appropriately, but also the process itself requires a sophisticated use, control, and extension of global computation schemes such as, e.g., the Finite Element Method.

First models such as proposed in [3] make use of a continuum model which captures the different states of the real material via strongly temperature-dependent material parameters. The implementation into standard FEM codes, as it has been conducted in, e.g., [2] by using the commercial software ABAQUS, requires the use of special subroutines to identify the respective state of the material—powder, molten, and re-solidified—depending on the current local temperature. In addition, the layer build-up has to be modelled appropriately, cf. [1].

The first enhancements of the present modelling framework comprise the definition of constitutive relations in terms of energy densities for each of the possible phases of the material. The overall material model is then based on a mixture rule and the temperature-induced change of the material's composition is obtained via energy minimisation and the associated determination of energetically favourable volume fractions of the powder, molten, and re-solidified phase. In this regard, the change of states of the material is treated as a classical phase transformation. The overall scientific aim is to establish a physically well-motivated material model which allows the accurate prediction of the effective material properties and, e.g., the simulation of process-induced eigenstresses of the manufactured workpiece.

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Micromechanics damage simulation of selective laser melting 316L stainless steel under monotonic loading

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Key Words: *Selective Laser Melting, Ductile Damage, Micromechanics, GTN Model, FE Simulation*

Selective laser melting (SLM) is a manufacturing technique, which allows free-form metal parts to be produced immediately after the structural design. Despite the evident advantage, there are still lots of unsolved problems, for instance, how the micro voids formed during SLM process influence the mechanical behavior and serviceability of the final parts, and this would be the major concern of the present paper. In order to understand the influence of the micro voids on the ductile damage evolution of SLM product under monotonic loading, several samples were produced from 316L austenitic stainless steel powder and tensile tests were performed. In addition to that, FE simulation was performed on the material model. The mechanical response of micro voids to the global monotonic loading was modeled by the Gurson-Tvergaard-Needleman (GTN) model. By simulation, the elastoplastic behavior, the ductile damage evolution of the material were analyzed and compared with conventional 316L grade. Beyond that, a sensitivity study of the model parameters were conducted of GTN model, and their influence of micro voids nucleation, coalescence and growth processes were evaluated separately on 316L material model. The GTN model is a suitable approach for micromechanics damage simulation of SLM produced 316L with micro voids, and makes it possible to investigate the relationship between micro voids and mechanical properties.

A numerical model to verify the electrical response of carbon fiber reinforced plastics in a three point bending test

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Key Words: *Three point bending test, Electrical response, Influence of damages, Resistance measurement, Finite element mesh, Carbon fiber reinforced plastics (CFRP)*

Additive manufacturing is being increasingly used to develop smart systems that have sensing and actuation functionalities. In particular it is possible to print conducting paths for structural health monitoring of carbon fiber reinforced plastics. Such printed paths can be used to monitor the change of electrical properties with respect to mechanical loading. Here, we build a numerical model to corroborate the electrical response of such a system of printed electronics on CFRP in a three point bending test.

The foundation of the present work is based on the results of Augustin et al. [1] on the online monitoring of CFRP using silver nanoparticle based ink. In that work, the inter-fiber failure was detected by measuring the resistance along single printed paths and inter-laminar delamination was detected by the change in through thickness resistance measurements.

In our work, we present a two-dimensional numerical model in COMSOL to evaluate the electrical properties of the system (e.g. resistance) depending on the number of damages. We adopted the original dimensions in [1] as an input for the geometry of the model. After constructing an appropriate finite-element mesh we obtained the change of electrical properties of the system with respect to the number of intra-laminar damages. For the experimental results, designated intra-laminar damages of fixed lengths were built into CFRP samples and the resistance measurements were performed using a four-point measurement with an impedance analyser. For the simulation results, these intra-laminar damages were modelled in COMSOL and the resistances were extracted. Different electrical parameters and intra-laminar damages were then varied until we found a good correlation between experimental and simulation results. In this contribution we will present the numerical model, experimental results and simulated values of resistances for various intra-laminar damages in CFRP.

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Development of technology for creating composite materials with several and original properties

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Key Words: *New Materials, Hybrid Properties, Multi Functions*

Since in the 21st century it has become more important to produce products with high quality [1], hybrid properties[2], multi-functions [3], low cost, eco-friendly [4] and many other properties, the most of manufacturers need several daring plans, unique ideas and new technologies. Therefore a software for creating new composite materials with hybrid properties desired by many designers was developed and evaluated. Young's modulus, density, coefficient of linear expansion, specific heat and thermal conductivity were calculated by a newly developed software. This software has two functions which are (1) the selection of adequate materials and the calculation of their ratios to achieve specific desired properties in a new composite material (2) the calculation of resultant properties given that the component materials and their ratios in a composite material are known. Particularly when the calculation to achieve the desired properties is performed, up to 5 properties can be requested at once (i.e. Young's modulus, density, coefficient of linear expansion, specific heat and thermal conductivity). Simultaneously, the order of priority and the permissible range regarding each property can be fed into the input of the software.

Thus, it is considered that this software can be effectively used for the design and manufacture of a new composite material with several hybrid properties.

It is concluded from the results that:

- (1) The proposed software could calculate Young's modulus, density, coefficient of linear expansion, specific heat and thermal conductivity for several properties.
- (2) The new system, with classification, penalty and loss function was developed for fine evaluation of the profitability.
- (3) Estimated values of density, coefficient of linear expansion and specific heat were each $\pm 5\%$, however those of Young's modulus and thermal conductivity were each $\pm 20\%$.
- (4) The software was very effective and useful for development of a new composite with several hybrid properties.
- (5) The tool post with composite material could decrease the probability of the chattering. And the tool post with composite material could improve the surface roughness of the workpiece in the shaving cutting.

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MULTI-PHYSICS AND
MULTISCALE-PROBLEMS IN
ADDITIVE MANUFACTURING

Microscale modelling for powderbed based laser melting: A testbed for new system technology

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Key Words: *Selective laser melting, Microscale simulation, Beam shaping*

Due to the high dynamics and small scales of the selective laser melting (SLM) process, experimental observations of the process itself are difficult to obtain. Therefore Gürtler et al. [1], King et al. [4] and Megahed et al. [5] each developed a simulation model of the SLM process at the microscale level to enable process analysis. Khairallah et al. [3] illustrate with the model of [4] different formation mechanisms for pores and spatter.

Spatter is often correlated to pore formation, since the size of spatter can exceed particle size and thus the chosen process parameters will fail to fully remelt the spatter depositions [6]. Kaplan deduces from observations that for the welding case spatter production can be divided into three primary mechanisms: melt flow-driven, vapour jet-driven and low boiling element-driven [2]. Due to the similarity of the processes, these mechanisms can be applied to selective laser melting as well.

We show an extension of the model of [1] and demonstrate how the modelling approach can be used to influence the development of new system technology and enhance the process quality. We improved the spatial discretization of the model to $\sim 1 \mu\text{m}$. In addition to the already established physical phenomena such as heat transfer, temperature and pressure driven melt flow, surface tension and phase changes and the inclusion of the according latent heat and energy transfer between the phases we also take into account temperature dependent material properties and the cover gas flow.

We propose to use spatial and temporal beam shaping to reduce the three spatter production mechanisms. The melt flow in conventional process strategies is induced by scanning of the laser beam, the thermal gradient and evaporation. Instead of scanning the build sample we employ spatial beam shaping techniques to irradiate large areas, thus eliminating the melt flow induced by the laser scanning. The thermal gradient is consequently reduced as well within the melt pool, lowering the whole melt pool dynamics substantially. Additionally we utilize temporal beam shaping to control temperature and prevent evaporation, eliminating the second and third spatter formation mechanisms.

Figure 1 shows the difference between the two process strategies. The left figure shows a conventional scanning strategy. Spatter is clearly visible. While the spatter particles are of small size and presumably do not influence the process, they are a sign of a high dynamic within the melt pool and a possible warning sign of pore trapping. The right figure shows a beam profile for a large area irradiation strategy.

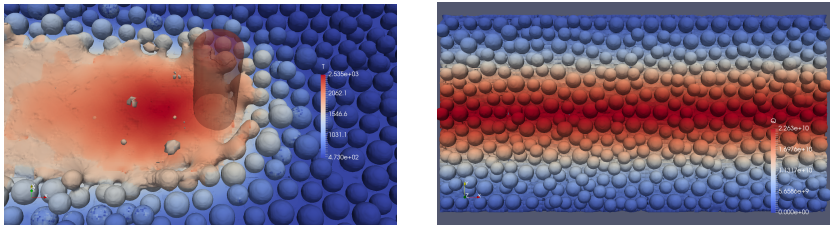


Figure 1: The left figure shows the conventional process with spatter production. The right figure shows a possible beam profile for a large area irradiation strategy.

An experimental investigation of this approach is currently limited due to missing high power spatial beam shaping devices. While there is no general physical restriction on employing optical devices (e. g. diffractive optical elements, electro-optical or acousto-optical deflectors) for high(er) power beam shaping, manufacturers have not yet seen an economical reason to develop them. We hope that showing the advantages of large area irradiation strategies will help to accelerate the academic and commercial development of such devices.

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Multiscale modelling of BCC Ti-Nb alloy sintered under conditions similar to additive manufacturing

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Key Words: *Multiscale Approach, Ti-Nb Alloy, Mechanical Properties, Computer Simulation*

The need for production of implants with an individual form leads to the necessity of developing new methods and approaches for their manufacture. The obvious advantages of using additive manufacturing and selective laser sintering are the possibility to create not only the external form of the product, but also its internal structure. Recently attractive in terms of biomechanical compatibility enhanced materials are alloys of titanium-niobium, which have similar properties to the elastic properties of cortical bone. In this paper, with use of multiscale approach a numerical study of the physical-mechanical properties of bcc titanium based alloys and their behaviour under conditions identical to the selective laser sintering was made. In the framework of first-principles method of exact muffin-tin orbital [1] the elastic properties of the bcc Ti-Nb alloy are calculated. An algorithm for optimizing of calculations has been proposed and approved. Using the molecular dynamics modelling [2], the changes of the structure of titanium and niobium nano-sized particles during melting process were studied. We also investigated the dependence of the adhesion properties of sintered nano-particles on the heating time of the system and its rate of cooling. It is shown that the main parameter, which determines the adhesive properties of sintered particles, is the contact area obtained during sintering process. Further step involves using the resulting information as input parameters for the computer model of the higher scale level. A numerical model on the basis of movable cellular automata method [3] is used to simulate the mechanical behaviour of the bcc Ti-Nb alloy specimen made under conditions similar to additive manufacturing. Various conventional tests like tension, bending and scratching are carried out in order to get new information about the material properties. Results of computer simulation are in good correlation with known experimental data.

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Multiscale modelling of the sintering process of printed nano-ink

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Key Words: *Sintering, Multiscale modelling*

In recent years plasmonic technologies have expressed needs for new economical, more-accessible and innovative ways to integrate electronic components in injection-molded plastic parts. The present work is dedicated to one particular technology called printed electronics; it is based on the selective laser sintering of printed metallic nanoparticle ink.

Numerical modelling is a must in order to investigate the adhesion of the metallic circuit on the plastic substrate while maintaining its integrity during the selective laser sintering process. Herein, multiscale thermal modelling is proposed to predict temperature evolution and distribution through both the deposit and the plastic substrate.

The multiscale approach combines two uncoupled models. First, a local model (Figure 1a) is used to characterize the effective thermal properties of nanoparticle charged ink by means of homogenisation. A finite element model of a representative volume element is used to model a number of silver particles embedded in ink. A thermal gradient is imposed to the domain through periodic boundary conditions and the effective thermal conductivity of the medium is computed. The level-set and the X-FEM methods enable solving the heat conduction equation without explicitly representing the particle-ink interface. A mesh adaptation step is performed beforehand in order to optimize the mesh size and hence increase the computational efficiency. Multiple runs with varying material properties and particle volume fraction help establish a new analytical mixture rule to predict effective thermal conductivity of nanoparticle ink.

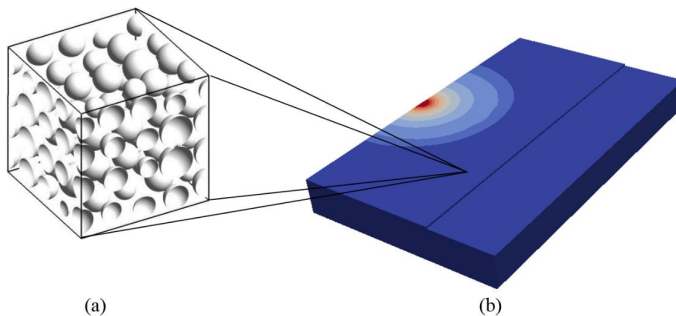


Figure 1 : (a) local model for the prediction of the effective properties of the nano-ink; (b) global model for the sintering simulation

Then this mixture rule is utilized within the so-called “global model” (Figure 1b), which simulates the sintering of the printed material. In this model, the metallic track is represented as a homogeneous material whose properties depend on the nanoparticle volume fraction. The vaporisation of the ink is also accounted for, which results in an evolution of the material properties during the process. The laser is modelled owing to a Beer-Lambert heat source, for which the optical properties of the nano-ink are measured experimentally. The purpose of the simulation is to determine the operational parameters, such as laser power and speed, which optimize the cost efficiency of the process, while ensuring an adequate electrical conduction of the sintered material and preserving the integrity of the flexible plastic substrate. Sensitivity analyses highlight the material parameters which have a prominent effect on the predictions, as well as the process parameters which can be tuned to optimize the process.

A multicomponent evaporation model for selective beam melting processes

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Key Words: *Selective electron beam melting, evaporation, fluid dynamics*

Powder-based additive manufacturing technologies such as selective laser melting and selective electron beam melting hold great promise for producing high-value metal components with customized geometries. Development of scanning strategies and prediction of optimal process parameters thereby remain key factors for the fabrication of high-quality products without local inhomogeneities in alloy composition or porosity. Especially in selective electron beam melting very high melt pool temperatures can be reached which leads to local depletion of volatile alloying elements, for instance aluminium in titanium alloys. In order to understand how the element loss and distribution is influenced by process parameters simulations were conducted on a mesoscopic scale that include melt pool hydrodynamics, thermodynamics and the mass- and energy loss as well as recoil pressure due to evaporation [1].

The relation between energy input, evaporation and residual porosity are numerically studied and different melting strategies are investigated. The line energy is of central importance, regarding evaporation losses, as it strongly affects peak temperatures during processing. Numerical simulations as well as experiments demonstrate that significant reductions in evaporation losses can be achieved by application of a suitable beam scanning strategy.

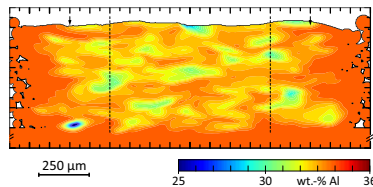


Figure 1: The picture shows a concentration distribution of a part of Ti-48Al-2Cr-2Nb build by electron beam melting with a beam power of $P = 600\text{W}$ and beam velocity $v = 3\frac{\text{m}}{\text{s}}$ as an example.

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How Can Exascale Computational Resources Accelerate Qualification of Additively Manufactured Parts?

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Key Words: *continuum dynamics, coupled physics, exascale computing, mesoscale modeling, multiscale modeling, phase field, upscaling*

Additive manufacturing (AM), or 3D printing, of metals is transforming the fabrication of parts by reducing the weight of final parts, reducing waste (and hence energy) in the manufacturing process, and dramatically expanding the design space, allowing optimization of shape and topology. However, there remain challenges in qualification of AM parts due to the unique physical phenomena inherent in AM processes. Although the physical processes involved in AM are similar to those of welding, a field with a wealth of experimental, modeling, simulation, and characterization research over the past decades, the failure rate for new AM parts is often as high as 80%. While modeling approaches and simulation tools for welding and similar processes are quite mature, and have been calibrated to the point that they are approaching predictive capability, they are proving to be inadequate for AM processes. We believe this is in part due to the fact that the process-structure-property-performance relationship is typically treated in an uncoupled manner, relying on tabular databases and hence unable to adequately capture the rapid dynamics and non-equilibrium nature of AM processes.

The Exascale Additive Manufacturing Project (ExaAM) is a collaboration between U.S. Dept. of Energy laboratories as part of the Exascale Computing Project¹ (ECP). ECP is a broad program including research efforts in hardware component and system design, system software, system acquisition and deployment, and science application development to deploy a computational ecosystem capable of delivering at least fifty times the performance of today's largest systems.

ExaAM is one of the applications selected for the development and implementation of models that would not be possible on even the largest of today's computational systems. With the prospect of Exascale computing resources in mind, one of the goals of ExaAM is to remove some of the limitations noted above by coupling high-fidelity sub-grid simulations within continuum process simulations to determine microstructure, properties, and hence performance using local conditions.

Figure 1 depicts the relevant physical phenomena in metal additive manufacturing processes, the focus of ExaAM. We briefly describe the overall goals and elements of ECP as well as the technical approach being taken in ExaAM, which involves integrating and extending existing physics

¹ <https://exascaleproject.org/>

components ([1], [2], [3], [4], [5], [6]), most of which were not developed specifically for AM but which include the relevant high-fidelity physics capabilities. We also discuss plans for verification and validation of this new integrated simulation environment through collaboration with efforts such as AM-Bench, a set of benchmark test problems under development by a team led by NIST [7].

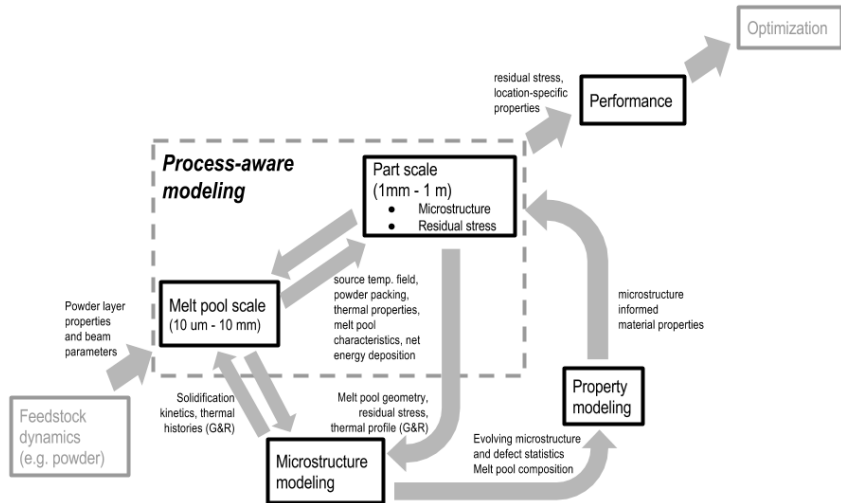


Figure 1: Physical phenomena in metal additive manufacturing processes.

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Thermal modelling of selective beam melting processes using heterogeneous time step sizes

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Key Words: *Process Simulation, Multi-Scale Methods, Thermal Modelling*

In the context of powder bed based additive manufacturing complex part geometries are realised in a layer-by-layer fashion and the fusion of powdered material in locally defined regions by means of e.g. a laser or electron beam. Simulating these manufacturing processes from a macroscopic point of view may lead to computationally expensive models, due to different scales in space and time, highly nonlinear material behaviour and methods to account for the layer wise built, i.e. dynamic growth of the computational domain. Aiming towards a reduction of the computational cost multiple numerical methods are therefore ought to be combined.

One approach in the context of Finite Element simulations is given by adaptive mesh refinement [3] and coarsening. This allows to locally refine the mesh where it is needed, e.g. in the region currently exposed to the beam, while keeping it relatively coarse in other regions. Yet the time step size of the model is constrained by the resolution of the beam path, which clearly limits the size of the problem under investigation. Within the present contribution we employ heterogeneous time step sizes to the arising thermal problem in different parts of the computational domain [2] in order to account for the distinct scales in time. In addition a line heat input model based on [1] is utilised to further lower the computational cost.

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Nonlinear finite element modelling and analysis of large repetitive lattice-type structures for additive manufacturing

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Key Words: *Lattice System, Large Repetitive Structure Numerical Modelling, Finite Element Analysis*

For many years now, Lattices Structures (SLs) are widely developed in the area of additive manufacturing which uses different types of materials (e.g. metals) for various applications in fields such as aeronautical, automobile, medical, ... Indeed, this forming process based on the material addition associated with successive layer stacking makes it possible to design structures that can combine both the innovation and aesthetics while coupling functionality, performance and robustness. As a result, SLs have the key advantage of being lightweight structures having in the one hand, an excellent weight/performance ratio and then in the other hand, extremely good physical/mechanical properties in terms of structural hold and resistance to strong external loads including shock and impact. From a general point of view, SLs belong to the class of repetitive (near-)periodic discrete structures (e.g. truss, foam, ...) with large or small sizes which can be modeled by several approaches more or less relevant depending on the type of structure in consideration. In the first part of this present work, a finite element modelling and analysis are proposed in order to test, assess and discuss the numerical capacities of both 3D continuum and beam elements for predicting both explicitly, efficiently and accurately the nonlinear mechanical behaviour of SLs [2]. The feasibility, validity and limitation of these two mechanical models are therefore presented through some numerical examples using a finite element software (Code_Aster). In the second part of this study, a numerical homogenization procedure is proposed for modelling the nonlinear macroscopic mechanical response including anisotropic compressive behaviour associated with these SLs [1]. The method used is based on the definition of a homogeneous equivalent medium where the homogenized macroscopic mechanical behavior is then determined under quasi-static uniaxial and multiaxial load conditions. Once again, the predictive numerical abilities associated with this numerical approach for providing an efficient and accurate macroscopic mechanical behaviour in regard to SLs are performed and evaluated on some specific examples with Code_Aster.

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Multiscale simulation of thermal behavior during selective laser melting of metals

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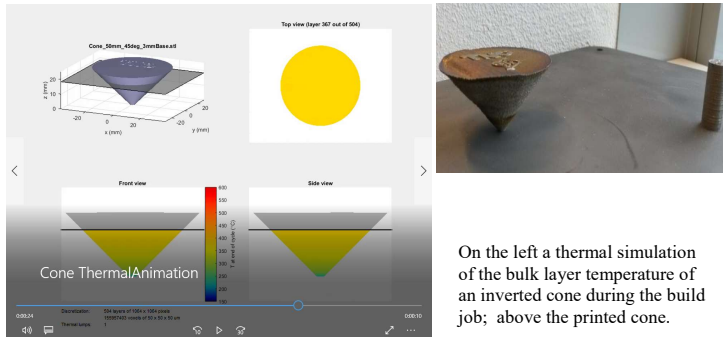
Key Words: *Thermal behavior, multiscale, simulation*

Introduction One of the key benefits of Additive Manufacturing (AM) is the possibility to produce complex integrated parts that would be difficult or impossible to produce with conventional manufacturing methods. However, without prior experience, it is hard to produce a complex part on a first time right basis. Typical issues during AM production are build failure due to internal stress in combination with a lack of supports, and geometric inaccuracies due to increased temperatures. These issues are related to the thermo-mechanical behavior of the material during the print process. Simulation of the thermo-mechanical behavior with, e.g., a Finite Element Method, gives insight in the process and allows for first time right manufacturing. As AM products are often one-of-a-kind, time effectivity of the models is of importance. Since there are magnitudes of difference in process time and length scales, the computational time can be prohibitively long. To this end, we propose a modelling method that separates two time and length scales in the thermal domain: in a coarse time and space simulation the temperature of each layer is calculated during the whole print job, and in a detailed simulation the local temperature of the melt pool is determined at the top layer. The results of both models are superposed to determine the variation in melt pool temperature during the print process. The results of the model can be used to redesign a product, change its orientation in a build job or to adapt the laser power to compensate for the changes in bulk temperature.

Model A lumped element model is proposed to predict the bulk temperature of each layer in the product during the print job. It is based on the assumption that the temperature gradient is predominantly in the build direction. Therefore, temperature gradients perpendicular to the build direction can be lumped in a single element for convex products. To further speed up the calculation process, a dynamic element size adaption scheme (based on the predicted heat transfer) is used. For powder bed fusion processes, a shell of powder around the product is represented by another lumped element per build layer. At the boundary of the powder shell and at the bottom of the product, the temperature is assumed to be constant and equal to the environment. Heat transfer can occur between neighboring layers in a single direction. The net absorbed power was determined by an experiment which also captured the loss due to radiation and convection at the top layer.

A more detailed model, based on an analytical heat transfer equation for a semi-infinite medium, is used to calculate local heat effects. This model assumes that the heat propagates through a single temperature invariant medium and was originally used to describe laser welding [1]. The model superposes the heat

propagation of a propagation point source. Combined, these models capture both the short and the long distance and time effects present during selective laser melting in a powder bed.



On the left a thermal simulation of the bulk layer temperature of an inverted cone during the build job; above the printed cone.

Verification and validation

The models have been implemented as a Matlab/C/Fortran co-simulation. Verification of the coarse model with a highly detailed Finite Element method shows the validity of the lumped capacitance approach in the large time and space scale.

For validation purposes, the models were used to predict the temperature of an inverted cone and a cylinder, among others. The calculation time for a 500 layer inverted cone was 600 seconds for all the lumped layers, and 2 seconds for the melt pool temperature of the final layer. These calculations were done on a laptop with an Intel Core i7-4800MQ CPU at 2.7GHz and 16GB RAM. The lumped model predicted that products with increasing areas, such as inverted cones, will increase in bulk temperature during the build job, whereas products with constant areas, such as a cylinder, do not.

The IR emission at two wavelengths was recorded during the build of an inverted cone and a rod using a melt pool monitoring system available in the Selective Laser Melting (SLM) machine. The melt pool monitoring system was calibrated using a thermocouple in a separate experiment.

Conclusion Two models are presented that capture thermal behavior on small and large distances and time scales for laser based additive manufacturing processes. These models were validated and can be used to improve the production yield and design of products, given the current executing time of the lumped model, we envision that real-time feedforward control of the melt pool temperature is possible.

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A Global/Local scheme for problems with steep moving gradients well-suited for reduction strategies

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Key Words: *Global-Local Schemes, Reduced Order Models, Steep Moving Gradients, Selective Laser Melting*

The aim of this work is to solve parabolic problems with steep moving gradients as those present in Selective Laser Melting in the neighbourhood of the heat source. A naive approach to tackle this kind of problems would be to refine the mesh as much as needed in all the regions of the domain that are in the vicinity of the path of the moving gradient. One alternative is to adaptively refine the mesh following the moving gradient. Despite the fact that both previous options are valid, both are very expensive and they are not so friendly to the formulation of Reduced Order Models (ROMs) because they do not help to tackle the space-time coupling of such problems [1].

The alternative proposed in this work is to adopt a Global/Local scheme, in which a moving local domain with a fine mesh describes the neighbourhood of the moving heat source and a coarse global mesh which describes the analysis domain. The coupling between the local and global domains is based on Lagrange multipliers which are defined only on the boundary of the moving local domain and no-remeshing is involved. The advantage of the proposed strategy is the possibility to reduce both the Degrees of Freedom (DOFs) of the local domain and the Lagrange multipliers DOFs, while exhibiting good robustness to the space-time separability issue.

In some applications, such as in Selective Laser Melting, important material phase changes take place. In a Global/Local scheme this introduces a complication which must be carefully studied. Therefore, another detail to be tackled in this work is the description of material phase changes in the moving local domain. In a series of numerical examples, the performance of the proposed techniques will be shown.

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Multiscale Modelling of Simple Geometry Printing via Powder Bed Fusion

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Modelling powder bed fusion processes involves resolution of several interacting physical phenomena. Laser irradiation is a key phenomenon driving powder heat up, melting and eventually the solidification of consolidated material. The thermal history of the work piece is usually complex both in space and time. The material shrinkage and clamping devices lead to residual stresses that affect the final workpiece shape. The final workpiece properties, the accumulated residual stresses and the overall distortions are complex functions of the input parameters: Powder and heat. Due to the complex physics encountered in powder bed fusion processes researchers sought to analyze single aspects of the manufacturing process. Körner et al. [1,2,3,4] focused on melt pool dynamics of selective electron beam melting. The models are based on Lattice Boltzmann methods and are mainly limited to 2D analysis. King et al. [5,6] utilized finite volume to resolve melt pool characteristics of laser based powder fusion. In this effort the laser absorption coefficients are derived from ray tracing studies [7]. Simpler models originating from the welding community were also used to predict the melt pool dimensions [8]. Kovaleva et al. developed a model based on heat and mass balances to predict the absorbed energy and melted bead size [9].

A larger group of researchers focuses on workpiece distortion. The resolution of the heat source track in a fully transient manner requires massive computational resources. The calculation of the workpiece distortions is thus pursued using simple models such as inherent plastic strain or instantaneous shrinkage [10,11,12,13,14,15,16,17].

There has been very little transfer of information from powder scale models to large scale models resolving workpiece residual stresses and distortion. Megahed et al. presented a multiscale multiphysics platform that resolves the heat source absorption, material phase changes (melting, evaporation and solidification), defects related to powder bed spreading and material consolidation as well as residual stress and distortion predictions [18,19,20,21,22]. Within the scope of this study the authors utilize this platform to investigate feature building in very high detail: The powder is spread numerically, the powder particles are molten to create the planar feature geometry, the consolidated material is cooled down to obtain the new geometry after shrinkage and the process is repeated again.

Figure 1 shows a sequence of images for 3 layers, each 25 μm thick. The feature to be build is the letter L. First the powder is spread onto the processing table, where a very low packing density is observed. The laser melts 2 long tracks and 2 short ones outlining the shape of the L feature. The increased surface roughness enhances the deposition rate during layer 2 coating process. The laser track is rotated by 60° and the L shape is traced using the new deposition strategy. At the end of layer 2 the L shape can be recognized much better in spite of the very thin consolidated layer thickness. The L shape interacts with the powder so strongly during layer 3 that the powder is densely packed in front of the L and is almost none existent behind it. The consolidated 3rd layer shows significant differences in build height. Where a lot of powder particles were deposited we observe a higher build than elsewhere.

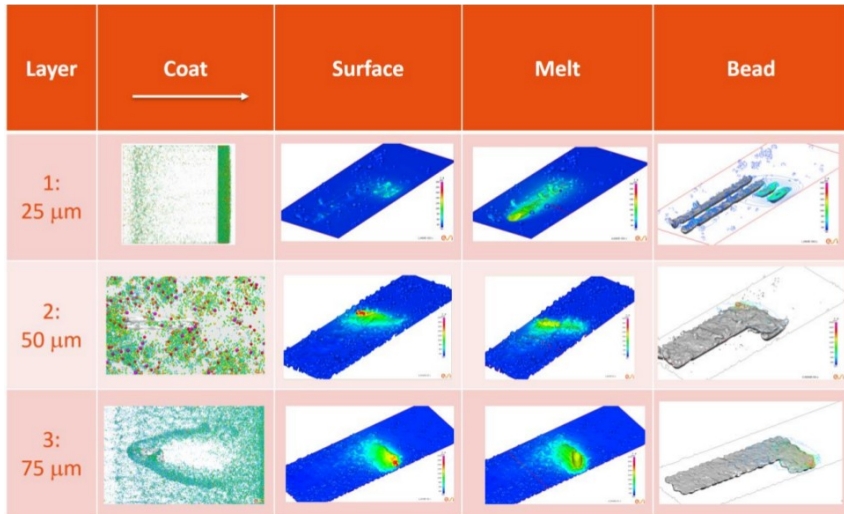


Figure 1: Images of final state after coating, melting and solidification after three layers, each 25 μm thick

The amount of data created is significant. Analysis of powder bed, melt pool characteristics and solidification is ongoing in parallel to the deposition of further layers. By the time this presentation is done more quantitative results will be available.

Acknowledgments

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Computational prediction of microstructure and magnetic property of additively manufactured magnetic materials

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Key Words: *Magnetic Property, Additive Manufacturing, Micromagnetic Simulation, Microstructure*

Exploring a strategy to predict the microstructure and property of additively manufactured (AM) materials or components is of great interests. Computational efforts in this direction are sustained along with the experimental support [1, 2]. Up to now, simulation or computational studies have been mostly focused on the metal-based structure materials, especially in the field of selective laser melting (SLM). In contrast, less efforts are made on the simulation of AM-fabricated functional materials such as ferroelectrics and ferromagnetics.

In this talk, we will present the computational prediction of microstructure and magnetic property of a typical magnetic material Fe–Ni alloy which is fabricated by the SLM-based AM process. The thermodynamically consistent microstructure prediction is performed by combining the thermomechanical model and CALPHAD (CALculation of PHase Diagrams). Information on the temperature dependent thermal conductivity, latent heat due to phase transition, specific heat, phase fraction, and phase composition in Fe–Ni alloy is obtained by employing CALPHAD method. Especially, magnetic contribution to Gibbs energy is also estimated. The temperature evolution, microstructure evolution, and stress evolution or residual stress are predicted. The SLM-based AM process parameters, such as powder composition and laser parameters, are further studied to show their influence. Taking the above-obtained microstructure and residual stress/strain distribution as an input, micromagnetic simulations are carried out to predict the magnetic properties of the SLM-AM produced Fe–Ni alloy, such as hysteresis curves, coercivity, remanent magnetization, magnetic domain evolution, etc. This talk presents the first-step attempt for the computational prediction of microstructure and functionality of additively manufactured magnetic materials.

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A simple and effective Timoshenko-like model for beams with complex geometry and variable infill.

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Key Words: *First order Shear Deformation Theory, non-prismatic and non-uniform beams, Fused Deposition Modeling objects*

Additive manufacturing technology is always more frequently exploited as rapid manufacture method and not only for the rapid prototyping [1]. As a consequence, designers must carefully consider not only the geometry, but also mechanical properties of the material. Focusing on Fused Deposition Modeling (FDM) 3D printed objects, it is worth recalling that they are composed by two main parts: an outer shell and the internal raster which mechanical behavior depends on several factors like the infill percentage, the deposition direction, the overlap between neighbor fibers, both the room and the extruding-head temperatures during the printing process, the filament dimensions, and so on. A recent paper [1] investigates the influence of several of the so far introduced parameters on the mechanical response of FDM 3D printed object, highlighting how deeply they influence the anisotropic mechanical properties of the material both in terms of strength and stiffness.

Furthermore, several of the parameters so far introduced can be locally modified, allowing for a point-wise optimization of the material micro-structure (and not only of the geometry). A careful analysis of such complex objects could be extremely expensive from the computational point of view and, since the optimization procedures are based on recursive analysis [2], the design process may turn out to be heavily weigh down. As a consequence, the development of simple and effective models for the analysis of such bodies is mandatory in order to reduce the computational costs.

Limiting the attention to beam-like bodies (i.e., 3D objects with one prevailing dimension), a simple model, capable to effectively tackle varying cross-section geometries was recently proposed [3]. Furthermore, [4] demonstrates that the approach is effective also in tackling continuous variation of the mechanical properties. In particular, every change between two subsequent cross-sections leads to non-trivial stress distributions that deeply influence both the stiffness and the strength of the object.

This contribution applies the so far introduced modeling strategy to several FDM 3D printed beams and aims at demonstrating that it is an effective tool for the analysis of such objects.

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Numerical methods for microstructural evolutions and mechanical property predictions in laser additive manufacturing

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Key Words: *laser additive manufacturing, Monte Carlo method, microstructural evolution, mechanical property prediction*

Laser additive manufacturing is recognized as a new technique for high performance complex manufacturing and has been quickly applied to industries [1]. The simulation of laser additive manufacturing can provide detailed insight into the microstructural evolutions in the additive manufacturing process. Monte Carlo method is efficient for predictions of grain growth in welding [2]. It can be also applied to field of laser additive manufacturing with combination of the heat source moving model [3] for laser additive manufacturing.

In the additive manufacturing, the temperature history and the microstructure of the 3rd layer is shown in Fig.1. When the laser is moving to the next layer, part of the current layer can be re-melted and other part reheated. The re-heating can lead to the grain coarsening in laser additive manufacturing of Ti-6Al-4V.

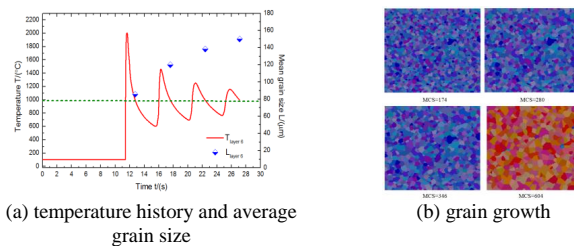


Fig.1 Temperature histories and microstructural evolutions in laser additive manufacturing

The needle-like α grains occur in high cooling rate in laser additive manufacturing of Ti-6Al-4V. To reveal the generations of needle-like α grain growth on the β grain boundaries, a smaller scale model is used with combination of the above mentioned Monte Carlo model of grain

growth in laser additive manufacturing. The cooling rate can affect the grain morphology of the α grain, as shown in Fig.2.

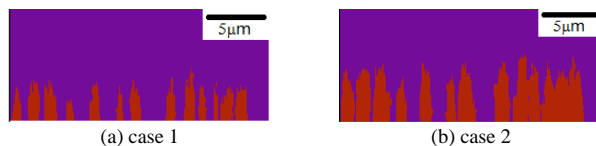


Fig.2 Needle-like α grain growth on β grain boundaries

The yield strength of $\alpha+\beta$ titanium alloy can be quickly estimated by a simplified model proposed by Zhang et al [4]. With combination of the microstructural evolution model, the flow stress of the obtained microstructure can be predicted, as shown in Fig.3.

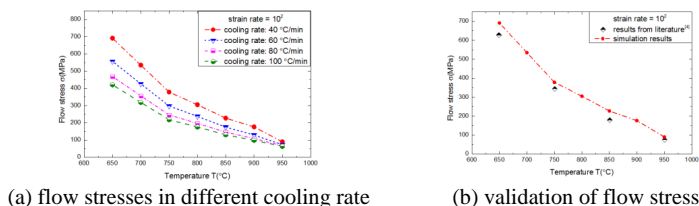


Fig.3 Predicted flow stress

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A combined model of surface growth and accretion based on the thermodynamics of irreversible processes

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Key Words: *surface growth; mass accretion; surface Eshelby stress; irreversible thermodynamics; bone external remodeling*

In physics, surface growth classically refers to processes where material reorganize on the substrate onto which it is deposited (like epitaxial growth), but principally to phenomena associated to phase transition, whereby the evolution of the interface separating the phases produces a crystal [1,2]. From a biological perspective, surface growth refers to mechanisms tied to accretion and deposition occurring mostly in hard tissues, and is active in the formation of teeth, seashells, horns, nails, or bones [3]. At a much larger scale, the dynamics of galaxies with mass loss due to either mass accretion or ablation provides another example of surface accretion, which has deserved a lot of attention in the literature for many years [4, 5], usually relying on an extension of Newton's law of motion [6], as originally stated by Sommerfeld in 1952. External (surface) growth or resorption in biological systems is a typical situation where the overall mass of a continuous body or a collection of particles varies, due to mass being apposed or resorbed at the system boundary; this process may involve a set of generating cells, either fixed (e.g. nails and horns) or moving (e.g. seashells, antlers) in space. Such systems with variable mass can be treated either from a discrete or continuum viewpoint, relying on the virial theorem for the situation [7].

A clear distinction is made in this contribution between accretion and surface growth, depending whether the aggregated material produces or not a new phase by internal mechanisms, as for instance in bone external remodeling in a biomechanical context. The following classification is adopted:

- Pure accretion without surface growth, with the meaning that the material deposited onto the surface does not generate new material *per se*. From a kinematic viewpoint, this means a nil growth velocity, so that the total velocity is the sum of the accretion velocity and an elastic velocity due to the development of both elastic surface and volumetric 'strains' leading to internal stresses. Surface accretion without surface growth can be illustrated in masonry constructions which are built up in successive layers of bricks in the presence of gravity loads [8].
- Accretion with concomitant surface growth is the more general situation - although specific to living tissues - requiring considering both a model for the accretion velocity of the set of generating cells, and a model for the surface growth process caused by the

generating cells. A typical illustrative situation in a biological context is bone external remodeling, which involves specialized cells removing and producing the new mineral phase forming new bone.

Based on this classification, we first analyze the situation of surface growth occurring in an elastic solid body, under the umbrella of the thermodynamics of irreversible phenomena. This leads to a consistent elaboration of a surface thermodynamic model including state laws for the configurational force, the chemical potential of superficial species and the entropy density, completed by kinetic laws governing the evolution of the internal variables. This model for surface growth extends the contribution [9] to the consideration of diffusion and surface mass production due to chemical phenomena. This framework is next enriched to the consideration of surface growth in presence of material accretion. This leads to the formulation of an incremental boundary value problem highlighting the crucial role played by the accretive traction responsible for the adhesion of newly apposed material, which incorporated a surface Eshelby stress as well as curvature.

Numerical simulations of bone external remodeling are performed to illustrate the general situation of combined accretion and surface growth.

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OPTIMIZATION AND ADDITIVE MANUFACTURING

Optimization-driven conceptual design tool for AM components

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Key Words: *design optimization, layout optimization, geometry optimization, additive manufacturing*

Additive manufacturing (AM) techniques are developing apace, and are now sufficiently mature to be used in the production of high value components. However to benefit from the unprecedented design freedoms offered, effective optimization techniques are required. Although topology optimization techniques have proved popular recent years, these are generally computationally expensive, particularly if a fine mesh is required in order to resolve fine detail when low volume fractions are involved (i.e. if the component occupies only a small proportion of the available design domain). Furthermore, topology optimization approaches normally require labour intensive post-processing in order to realise a practical component, often leading to long and labour intensive workflows.

In this contribution it is shown that layout optimization (LO) can be used in conjunction with geometry optimization (GO) to provide the basis for a powerful and effective conceptual design tool for AM component designers, building on previous work in this area [1, 2]. The approach is particularly useful when the degree of design freedom is high, where truss-like forms are typically found to be very structurally efficient. With LO the design domain is discretized using a grid of nodes which are interconnected with discrete line elements. Linear optimization is used to identify the subset of elements forming the minimum volume structure required to carry the applied loading. GO, which involves adjusting the positions of the nodes using non-linear optimization step, can subsequently be undertaken to simplify and improve on the solution. Simple rules can then be used to automatically transform a line element layout into a 3D continuum. The various stages involved in the process are shown in Figure 1. Smith et al. [2] demonstrated the efficacy of the basic approach, manufacturing various component designs in titanium Ti-6Al-4V using the electron beam melting process, and performing load tests to show that target load capacities could be attained.

As solutions can be obtained very rapidly using the approach described (often in a matter of seconds on a modern desktop PC) it can be incorporated in interactive CAD software tailored for use at the conceptual design stage. Also, because of the high-level nature of the solutions generated (which involve members and joints, rather than low-level meshes), these can readily be interactively modified by the user, and

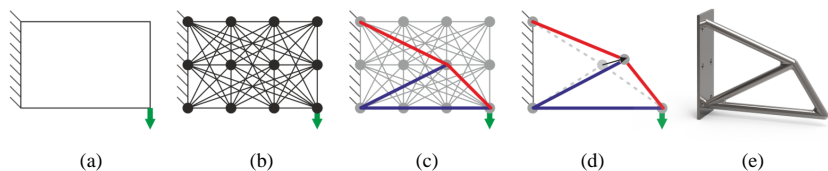


Figure 1: Stages in the optimisation process: (a) design domain, loads & supports; (b) nodes distributed across the design domain & potential truss element connections; (c) resulting minimum volume truss; (d) positions of nodes modified using geometry optimisation to further improve the result; (e) truss elements replaced with solid elements (e.g. cylinders) and joints added to create a watertight volume

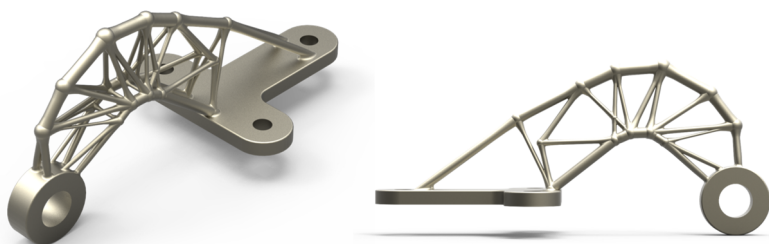


Figure 2: New design for Bloodhound SSC airbrake hinge

further optimized if required (i.e. as part of a ‘human-in-the-loop’ optimization process). This allows a range of issues not included in the original optimization formulation to be taken account of (e.g. aesthetic and/or practical considerations). Interactive software incorporating the approach described has recently been developed [3] and has been applied to a range of practical design problems. Figure 2 shows a new airbrake hinge design for the Bloodhound supersonic car generated using the software. This design is simpler than the design described by Smith et al. [2] yet is still approx. 70% lighter than the original, non-optimized component, clearly demonstrating the efficacy of the approach.

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B-spline Based Topology Optimization for Metal Hybrid Additive-Subtractive Manufacturing

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Key Words: *Topology Optimization, Hybrid Manufacturing, B-spline*

Hybrid additive-subtractive manufacturing is an emerging technology, which is capable of fabricating complex raw part through additive manufacturing (AM) and then finishing the part to meet surface and dimensional requirements through subtractive machining [1]. Therefore, a large design space could be explored to ensure design creativity, and the derived size, form, and surface quality satisfy engineering requirements.

However, there are key current issues that are impeding the marriage between hybrid manufacturing and topology optimization: 1) Inability to connect the topology optimization result to commercial CAD system for post-editing, 2) Difficulty in post-machining topology optimized AM parts due to their highly complex shapes, and 3) Uncontrollable expense in manufacturing because of cost information absence in the optimization problem formulation.

To fix these issues, this research contributes a B-spline based topology optimization method capable of interfacing commercial CAD systems, accounting for post-machining requirements, and also effectively controlling the overall manufacturing cost. Specifically, both the B-spline control points [2] and feature modeling history will be adopted as the shape and topology variables, because under the B-spline based topology optimization framework, starting from different feature modeling histories will lead to distinctive design results. A ‘feature modeling history’ topological derivative concept is proposed and highlighted as a novel approach to switch feature modeling history during the optimization process. Consequently, both the B-spline information and feature modeling history are important assets to interface CAD for user-friendly post-editing. Moreover, the topology optimized AM component would be composed of only machining-friendly surfaces, which can be economically and efficiently finished by pocket machining [1] and 3-axis freeform machining. Other than that, a cost estimation function is established based on the B-Spline information and the employed hybrid manufacturing process [3,4]. It will be embedded into the formulation of the optimization problem, through which the overall manufacturing cost can be approximately constrained below the expected limit.

In summary, the technology developed will significantly shorten the design phase during new AM product development, which will potentially lead to wider adoption of AM. Effectiveness of the proposed method will be proved through studies of several real parts.

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Topology Optimization of Anisotropic Components for Additive Manufacturing

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Key Words: *Topology optimization, anisotropy, Tsai-Wu failure criteria*

Although topology optimization (TO) and additive manufacturing (AM) have flourished independent of each other, there is significant interest today in integrating the two for several reasons: (1) designs stemming from TO are geometrically complex, and therefore hard to manufacture using traditional processes, but can often be additively manufactured. (2) the cost of fabricating parts through AM is proportional to the amount of material used, and material usage can often be reduced through TO, and (3) through TO and AM integration, one can potentially develop an automated pipeline from design concept to fabrication.

While these and other characteristics make TO and AM ideally suited for each other, there are several challenges that must be addressed. Material anisotropy and weakness along build direction, especially in AM processes such fused deposition modeling (FDM), is one such weakness. Material anisotropy is often neglected during TO, and the optimized designs will not perform as expected.

Material anisotropy manifests itself in two forms: (1) anisotropic constitutive properties that relate stresses and strains, and (2) anisotropic strengths that relate to the failure of the part. The focus of this talk is on the latter, i.e., anisotropic strength.

In TO, recall that for *isotropic* materials, the von Mises stress is often used as the failure criteria. This criteria is invalid for anisotropic materials, instead the Tsai-Wu stress criteria is proposed. Appropriate sensitivity analysis using Tsai-Wu stress criteria will be discussed, and a simple TO algorithm will be proposed for optimizing components with anisotropic strengths.

As a specific example, we will consider the strength summarized in Table 1 [2]. Observe that the strength along the build direction (Z) is 30% smaller than the strengths in the X and Y directions.

Table 1: Material strengths

Material	Xc (MPa)	Yc (MPa)	Zc (MPa)	Xt (MPa)	Yt (MPa)	Zt (MPa)	Syz (MPa)	Szx (MPa)	Sxy (MPa)
ABS (FDM)	38	38	35	29.62	29.62	<u>19.80</u>	10	10	10

To demonstrate the impact of the stress criteria, consider the C-bracket problem in Figure 1; the domain is discretized into 20,000 hexahedral elements. The objective is to find the strongest design while removing 50% of the material. Figure 1b illustrates the optimized topology using *isotropic von Mises criteria* with a yield strength of 25 MPa, while Figure 1c illustrates the optimized topology using the Tsai Wu criteria using the relative directional strengths summarized in Table 1.

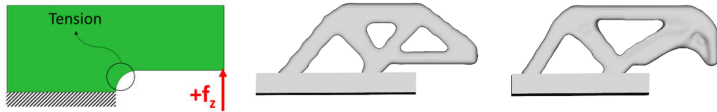


Figure 1: (a) Geometry and loading, (b) optimized using von Mises criteria, (c) optimized using Tsai-Wu criteria.

Four samples of each of the optimized designs was printed on an XYZ FDM printer with the same printing parameters. Then, a custom fixture was designed to carry out failure tests. Figure 2a illustrates the test setup, and Figure 2b illustrates the experimental results. As one can observe the part optimized using von Mises criteria fails much earlier than the one optimized using Tsai-Wu criteria. This suggests the importance of using the appropriate stress criteria for anisotropic materials. Future work will focus on other aspects such as debonding or brittle failure.

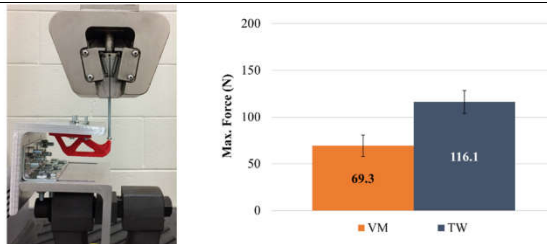


Figure 2: C-Bracket experimental set-up and results.

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Topology optimization of part and support structures for additive manufacturing considering machining forces

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Key Words: *Topology optimization, additive manufacturing, overhang angle, support structure, machining, design for manufacturing*

Topology optimization is universally recognized as the key design method to fully exploit the tremendous design freedom offered by additive manufacturing (AM) techniques. However, classical topology optimization approaches do not consider specific restrictions of typical AM processes. From a design-for-manufacturing viewpoint, ideally all restrictions of the manufacturing process are already included at the design stage [1]. One such restriction present in many AM processes is the maximum overhang angle of downward-facing surfaces of a part. Surfaces that violate this restriction need to be supported by sacrificial support material. This adds costs in terms of material consumption, extra build time, and labor costs for the support removal process. Taking these extra process-related costs into consideration in the part design phase is therefore desired.

In past research, we have proposed a topology optimization formulation including an AM filter, emulating a simplified layer-by-layer manufacturing process [2]. This formulation generates fully self-supporting parts for a given build orientation, i.e. parts free from surfaces violating the critical angle. As a result, the optimized part can be produced without adding support material to meet the overhang criterion. Focusing exclusively on fully self-supporting designs however restricts the design space, and this can result in decreased performance. To allow for trade-off solutions that balance performance and costs, an extended formulation was proposed where the optimization process could still introduce a suitable amount of supports [3].

In this contribution, we extend our design-for-AM topology optimization procedure with the consideration of machining forces. This particularly targets powderbed-based metal AM (e.g. SLM, SLS), which are presently used for most printed metal end-use parts. Subtractive machining (e.g. milling, drilling, tapping) after the build process is commonly necessary, to e.g. reach the specified surface roughness and tolerances on contact surfaces, as present metal AM technology lacks the required resolution. A typical practice is to machine the part while it is still connected to the base plate. The stiffness of the part in this configuration should be sufficient to suitably limit the deformations due to machining loads, in order to reach specified tolerances.

Hence, when post-build machining is considered as part of the fabrication process, support material has a double function. It may be needed to support overhanging regions, but it also serves to firmly connect the part to the base plate, to ensure sufficient stiffness during the machining operations. This can lead to different trade-off solutions compared to design approaches only focusing on the overhang aspect. Based on the AM filter, we computationally form the as-built structure consisting of part and supports during the optimization process, and evaluate its stiffness in the defined machining load

cases. By adding this as compliance constraints to the topology optimization problem, both part and support layout can be optimized simultaneously while meeting the demands of critical overhang angles as well as machining-related criteria. The objective of the optimization process is a combination of part performance in a defined service load case, and a cost term related to the amount of support material. The approach is demonstrated on 3D numerical examples, with a preliminary result depicted in Figure 1.

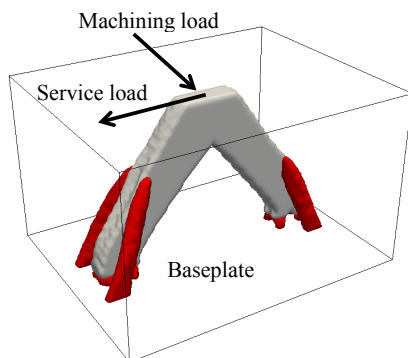


Figure 1: Preliminary example of a design obtained by combined topology optimization for AM overhang restrictions and machining load requirements. The part geometry optimized for minimum in-service compliance is shown in gray, and the sacrificial support material is shown in red. A 45° critical overhang angle was assumed.

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Novel approach for the optimization of support structures and integration into Amphyon

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Key Words: *Process Simulation, Support Optimization, Process software*

1 Introduction

As the integration of powder based Additive Manufacturing into industrial production increases, challenges such as geometric accuracy, production cost and automation of the process chain gain in importance. In this context, an automatic generation of support structures that reduces geometrical deviation, material usage and process time remains one of the key objectives in software development for Additive Manufacturing. The presented work derives and evaluates a novel approach for the fully automatic simulation based optimization of support structures.

2 Optimization Approaches

Existing Approaches

A major obstacle during the optimization processes of AM and other complex processes is the resulting computational time for conventional optimization approaches such as. Such approaches rely on a high number of calculations of the objective functions, which in case of additive manufacturing, would result in a large number of process simulations and unfeasible calculation times. Most approaches for the optimization of support structures in AM therefore focus on the iterative adjustment of support structures based on failure criteria. On the downside, such approaches tend to neglect the aspect of minimizing the process induced deformation by support structures

Presented Approach

The main focus of the algorithm is the minimization of process induced deformation and material usage, while constraints on the stability of supports can also be integrated into the presented approach. In addition to the part geometry, defined as $\Omega_p \subset \mathbb{R}^3$, and fixed process parameters, such as the used material and machine, the optimization also relies on a previously defined design space for the supports $\Omega_s \subset \mathbb{R}^3$ as well as the definition of basic properties of the cellular structures as for example beam or wall supports. For a given number of degrees of freedom for the support generation N_s , let $h \in \mathbb{R}^{N_s}$

denote the support parameters. For a fixed support design, defined by h , let $u(h) \in L^2(\Omega_p)^3$ denote the deformation restricted to the part domain as it is induced by the AM process. Finally let $M(h)$ be a function that describes the material usage within the supports defined by h . The optimization term then is given by

$$\min_{h \in \mathbb{R}^{N_s}} \left[\|u(h)\|_{L^2(\Omega_p)^3}^2 + \alpha M(h) \right],$$

with additional constraints that provide a minimum support density as well as process stability by integration of failure criteria as described above.

3 Results

The algorithm has been implemented and applied to a number of geometries of varying complexity. Figure 1 shows preliminary simulation based results with two original part geometries and their pre-defined support regions on the left side and the resulting optimal supports, represented by their respective density, on the right. As can be seen in both cases, the algorithm generates support structures that reduced both the deformation norm and the estimated material usage when compared to the the simulation with uniformly distributed supports.

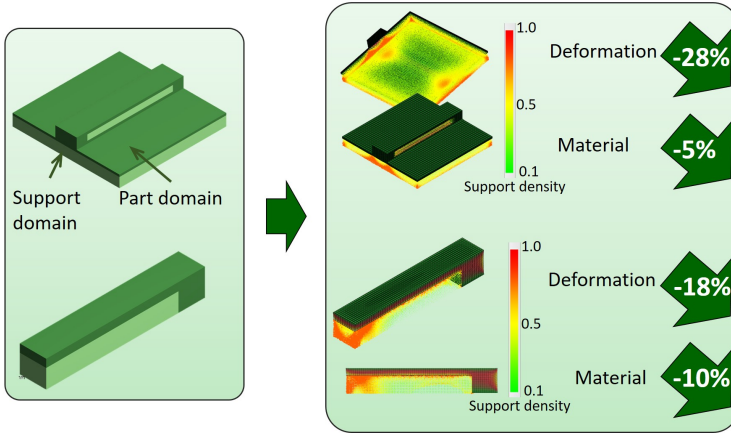


Figure 1: Optimization routine applied to different parts

4 Conclusion

The presented approach provides a means to optimize cellular support structures in Additive Manufacturing by automatic FE-based simulation and has the potential to reduce process and development costs as well as increase geometric accuracy of parts.

Remarks on Additive Manufacturing Constraints in Topology Optimization

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Key Words: *Additive Manufacturing, Topology Optimization, Printing Angle*

Additive manufacturing is a layer-by-layer printing process, which builds a part from the bottom up. Although it provides a new horizon for manufacturing technology, it also anticipates several limitations. One of the important challenges in additive manufacturing is that it requires support structures in order to print an inclined surface. Once finished printing, these support structures are removed by additional processes. Due to the complexity of structures, however, it is difficult and expensive to remove the support structures, especially when they are located inside. Therefore, it would be advantageous if a structure is designed in such a way that it does not require any supporting structures or minimizes the usage of them.

In this paper, a simple strategy of imposing additive manufacturing constraints at the level of an individual element is discussed, which guarantees that the material density of an element should be less than or equal to that of supporting elements. Referring to Fig. 1(a), the current element ‘e’ has an array of supporting elements (showing in gray color). The supporting elements are selected based on the angle between the current element and a candidate of supporting elements. Let \mathbf{n} be a unit vector in the printing direction, and \mathbf{d}_{ij} be a vector from the center of the i -th adjacent element to the center of the current element j . Then the supporting elements can be defined for those elements whose angle is less than the printable angle, θ_{ALM} . Normally $\theta_{\text{ALM}} = 45$ degree, but it can be user-defined.

When current element j has M number of supporting elements (see Fig. 1(a)), the maximum density of supporting elements can be defined as $\rho_{j,\text{supp}} = \max(\rho_1, \rho_2, \dots, \rho_M)$. Then, the density of current element has to be modified by $\rho_{j,\text{NEW}} = \min(\rho_{j,\text{supp}}, \rho_j)$ [1]. This means that the current element density cannot be larger than the density of supporting elements. This is the state-of-the-art strategy to impose the additive manufacturing constraint proposed by Langelaar [1] and Gaynor and Guest [2].

Since $\max()$ and $\min()$ functions are discontinuous, these functions can be approximated by a continuous function, such as a smooth maximum approximation [3]. As with most approximation methods, the smooth maximum approximation converges to the $\max()$ or $\min()$ function as its parameter increases. However, nonlinearity increases proportionally to the parameter, which makes the optimization algorithm difficult to converge. Therefore, an adaptive strategy is used to increase the parameter gradually such that both stability of optimization process and accuracy of additive manufacturing constraint can be maintained.

An important issue in the above-mentioned method of imposing additive manufacturing constraints is that $\rho_{j,NEW}$ satisfies the additive manufacturing constraint against ρ_j [2]. However, that does not necessarily mean $\rho_{j,NEW}$ satisfies the constraint. As shown in Figure 1(c), individual element density $\rho_{j,NEW}$ satisfies the additive manufacturing constraint against the distribution of ρ_j in Fig. 1(b). However, the distribution of $\rho_{j,NEW}$ does not satisfy the additive manufacturing constraint. This is the major disadvantage as the constraint may not satisfy even after imposing the above-mentioned conditions. In order to satisfy the additive manufacturing constraints in all $\rho_{j,NEW}$, it is necessary to impose the constraint by defining the maximum of supporting elements as $\rho_{j,supp} = \max(\rho_{1,NEW}, \rho_{2,NEW}, \dots, \rho_{M,NEW})$. However, this is in general not possible because of the updating method of $\rho_{j,NEW} = \min(\rho_{j,supp}, \rho_j)$. In this paper, this challenge is easily overcome by ordering all elements in such a way that the update of element density is done in the printing direction. Then, all supporting elements are updated before updating the j -th element.

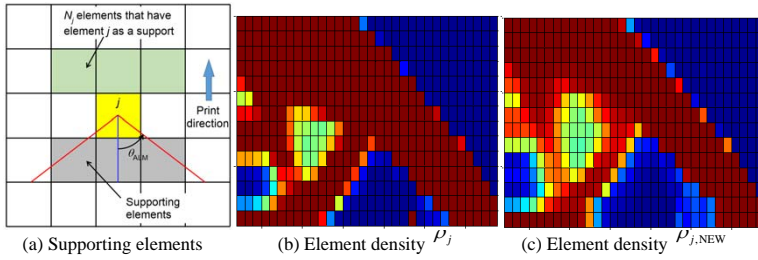


Figure 1: Supporting elements for additive manufacturing constraint

The additive manufacturing constraint can be considered as a projection. That is, a given element density ρ_j is projected to $\rho_{j,NEW}$ to satisfy the constraint. In the case of a projection, optimization is performed on the original density ρ_j , while performances (objective and constraints) are calculated using $\rho_{j,NEW}$. Therefore, the sensitivity of a performance g with respect to the original density ρ_j is required. By differentiating the projection, the following sensitivity expression can be obtained:

$$\frac{\partial g}{\partial \rho_j} = \frac{\partial g}{\partial \rho_{j,NEW}} \frac{\partial \rho_{j,NEW}}{\partial \rho_j} + \sum_{i \in N_j} \frac{\partial g}{\partial \rho_{i,NEW}} \frac{\partial \rho_{i,NEW}}{\partial \rho_{i,supp}} \frac{\partial \rho_{i,supp}}{\partial \rho_{j,NEW}} \frac{\partial \rho_{j,NEW}}{\partial \rho_j}$$

In the above equation, N_j is the number of elements that include the current element j as a supporting element. The sensitivity of performance with respect to the projected density, $\frac{\partial g}{\partial \rho_{j,NEW}}$, can be calculated using the conventional adjoint variable method.

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Computational time issues of AM process simulations with a view to large-scale topology optimization

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Key Words: *AM process simulation, topology optimization, computation time*

Including detailed simulations of complex manufacturing processes in a design or optimization loop is gaining allot of attention, in particular with regard to additive manufacturing (AM). A key driving force behind AM is the geometric freedom granted to the designer, which enables innovative designs of high complexity. However, given (i) the high-energy input typically associated with AM processes, (ii) the multi-physics and multi-scale phenomena that need be accounted for, (iii) the necessity of support structures and subsequent machining steps and (iv) the complexity of the geometry itself; a human designer is no longer able to account for the sheer number and entanglement of design and manufacturing considerations. Therefore, in order to exploit the advantages of AM, large-scale structural optimization techniques—*i.e.*, topology optimization [1]—in combination with numerical process simulations, are required.

The feasibility of the automated avenue of design and manufacture, as outlined above, hinges first and foremost on the computational efficiency of the AM process simulation, and the associated design sensitivity computations. Moreover, AM process simulations in general follow the additive nature of the physical process itself, and therefore involve growing computational domains. In a finite element setting, new elements are added or activated in the FE model and the degrees of freedom increase in each time step of the process simulation. This aspect typically necessitates advanced computational implementations and has implications in terms of computational scalability of the simulation and, by implication, the optimization phase [3].

In this contribution, we consider options for reducing the computation— or wall-time of the AM process simulation part of the problem. The work is based on a layer-by-layer process model, with the energy input associated with the AM process simplified to thermomechanical loads [2]. Initially, geometric and material linearity is assumed, although the computational implications of including nonlinear phenomena and more complex loading conditions—including, for example, heat transfer simulations—are investigated as well.

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Complexity is Free, But How Can We Benefit from It?

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Key Words: *Topology Optimization, Microstructured Structures*

Additive manufacturing techniques have evolved to allow material composition to be built by region, by layer, or point-wise. Graded or cellular materials and structures with high complexity can be fabricated without the restrictions of the conventional manufacturing processes. Complexity is free (or almost).

But, designing complex materials and structures to gain benefits in mechanical and structural performance in terms of the complexity in topology, distribution of constituent material phases and even material microstructures is a challenging problem. In order to take full advantage of the greatest potential of architecture structures, one must have matching capabilities for their computer modeling, analysis and design optimization. In this paper, we first discuss the issue of geometric complexity vs. material complexity. We then present an approach based on a multi-phase level set model for the geometric and material representation. The level-set framework yields a multi-scale model for addressing topology, geometry, material composition, and even microstructures of a functionally gradient structure. We present examples for the optimization of microstructured elastic structures with variable level of complexities.

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Topology optimization for lattice structure design

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Key Words: *Lattice Structure, Topology Optimization, Additive Manufacturing*

Cellular space filling materials have been used for many years in different applications to improve weight saving, energy absorption or to exploit other special characteristics like heat dissipation efficiency. Until the recent years, the majority of cellular material use has been relying on foams, and spread mainly in applications related to panels for constructions in civil engineering, mechanical and aero-space industry [1, 2]. However, with the recent advances in Additive Manufacturing, a different type of cellular material is rapidly gaining ground, referred to as Lattice structures. Lattice structures are porous materials produced by repeating a unit cell throughout the structure and by varying their density and size desired local and global mechanical properties can be achieved.

Though the lattice structures as such have been studied in depth, in terms of their individual design [3, 4], their mechanical performance [5 – 8], the complete workflow of designing a structural component with lattice structures is rarely looked upon. In the design specific aspect, most of the research focuses on optimizing the truss diameters of a given lattice design for best mechanical performance [9, 10], however, these approaches assume an already existing volume of lattice structures.

The authors propose a methodology, supported by software tools, which doesn't only focus on the optimal sizing of the lattice structures for obtaining the highest structural stiffness, but also defines where lattice structures are needed in order to provide the best mechanical performance with the lowest possible weight.

The methodology relies on topology optimization adapted to drive lattice structure design. As presented in Figure 1, first the design space is prepared for topology optimization. Next, topology optimization is performed considering the actual material properties of a selected lattice cell type. Furthermore, the zones designated for lattice and bulk material are defined considering the printability of the lattice structures with powder bed based additive manufacturing process. Additionally, the rough geometry resulting from topology optimization is post processed to obtain smooth and conformal surfaces. Next, lattice structures are generated in the target zones for lattice material and their trusses are sized based on the results of topology optimization.

Finally, finite element analysis is used to assess the structural mechanical performance of the obtained lightweight design.

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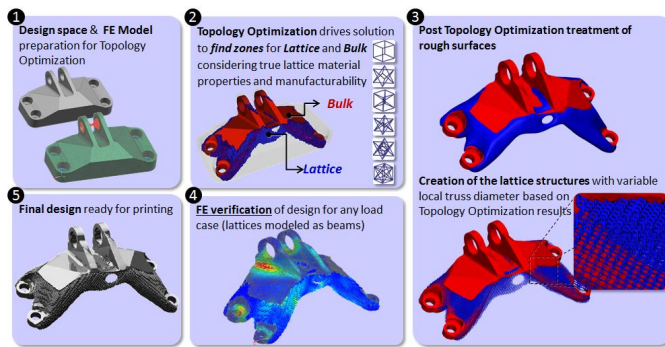


Figure 1 Topology optimization for lattice structure design

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Design of Unstructured Lattices by an Adaptive Topology Optimization Process

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Key Words: *Lattices, Topology Optimization, Additive Manufacturing, Adaptive Process*

Additive manufacturing now allows the conception and fabrication of lattice structures as alternatives to solid parts (see Figure 1). These structures present the advantages of featuring good mechanical properties while being lightweight, which is of interest for example to the aeronautics industry. Lattice structures also draw a lot of attention in biomedical applications as they exhibit better biocompatibility than conventional materials when employed as prostheses.

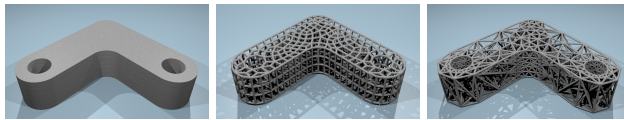


Figure 1: Solid part (left), structured lattice (center) and unstructured lattice (right)

The design of lattices present several challenges due to the extended freedom provided by additive manufacturing technologies. More precisely, one has to precisely define the position and size of the trusses composing the lattice. This can be achieved by creating a conformal lattice (Figure 1, center), but such a choice is often sub-optimal with respect to design requirements (e.g. minimal mass, maximum deflections and constraints). Therefore, our goal is to solve a topological optimization problem in order to obtain an optimal design, which can be an unstructured lattice (see Figure 1, right).

We address the topology optimization problem by choosing some parameters of the trusses (e.g. position, size) as the variables of the problem. To reduce the number of degrees of freedom, we employ unidimensional models such as the bar model or the Euler-Bernoulli model to describe the mechanical properties of the lattice. Finally, in order to search in a smaller design space, we adopt an adaptive process. We solve the topological optimization problem on a coarse lattice (with few trusses) and we gradually add new trusses in relevant regions. We will present the theoretical framework of the adaptive method and show the performance of the approach on some numerical examples.

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Topology optimization of elastic cellular structures by the homogenization method, using isotropic cells

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Key Words: *Topological Optimization, cellular structures, additive manufacturing*

We present here a topological optimization method by the homogenization. On one hand, in a large number of shape optimization problems, composite structures, which are mathematically the limits of classical micro-perforated shapes, are known to reach the optimum. On the other hand, the improvement of additive manufacturing (AM) technologies makes possible to manufacture structures with very complex topology. Consequently, we are interested to design optimal quasi-periodic structures, composed of a given family of perforated cells.

A classical optimization problem in elasticity consists in capturing an optimal distribution of matter Ω in a work space D , which minimizes the compliance of the final structure Ω under the constraint of a fixed volume. Here, thanks to the homogenization method, we are interested in finding an optimal distribution of composite cells, parametrized by a finite number of parameters p_i : our variables of optimization are then the fields $p_i \in L^\infty(D, \mathbb{R})$.

We studied here the optimal cellular structures composed of periodic cells, isotropic in 2D and quasi-isotropic 3D [2]. Their homogenized elastic behavior depends only on their density. Thanks to the homogenization method [1], we can easily compute the homogenized elastic tensor of any cell, and its derivative, by solving the so-called cell problems. Then, by interpolation, we reconstruct the homogenized Hooke's tensor in function of the density of the cells. Thanks to a projected gradient algorithm, an optimal composite shape is found, defined by the optimal homogenized fields of parameters.

Then, we extract from this composite shape a quasi-periodic and AM-manufacturable structure: we fix a size of cells and project the density on each cell. A post-treatment is used to ensure smooth link between the cells. Our method has been successfully tested in 2D and in 3D, and for different optimization problems: simple and multiple load compliance, maximization of eigenfrequencies, gripping mechanism. Prototypes have been successfully printed.

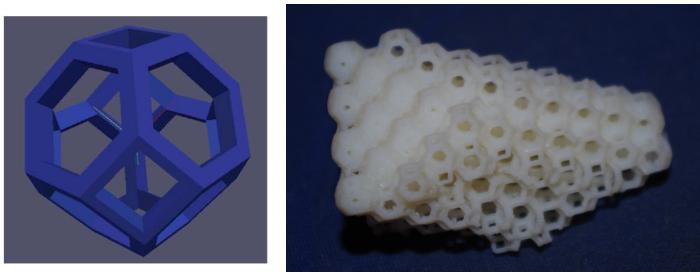


Fig. 1: (left) Quasi-isotropic cell: Tetrakaidecahedron
(right) Half optimized cantilever printed structure

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Different Structural Optimization Advances for Industrial Additive Manufacturing Designing

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Key Words: *Structural Optimization, Non-linear modeling, Adjoint sensitivities, AM constraints*

The current work presents the latest industrial solutions and workflows offered and being developed by Dassault Systèmes for additive manufacturing and designing with a special focus on topology and sizing. Here is essential to notice that Dassault Systèmes has several multi-brand solutions with very tight integrations between the various solutions powered by the **3DEXPERIENCE** platform. Therefore, the **3DEXPERIENCE** platform is a strong End-to-End solution for designers of additive manufactured components where the users do not have to differentiate rigorously between the CAE-process (finite element solutions), topology optimization-process and the CAD-process. The following work will focus on some of the many new advances for industrial additive manufacturing designing for the present workflow obtained in the field of the CAE-process and optimization-process.

One advance is to consider an additive manufacturing constraint for topology optimization in the form of an overhanging constraint, see figure 1. An overhanging constraint ensures that the optimized structures are printable up to a certain minimum angle, depending upon the material and printing technique. The overhanging constraint for topology optimization is formulated as geometrical constraint. Most important for industrial CAE models the present geometrical constraint allows unstructured meshes (e.g. triangular or tetrahedral meshes), various objective functions and constraints typically applied in industrial applications (e.g. minimize mass with stiffness, strength and modal eigenfrequency constraints). Additionally, the optimization solution is integrated with a general non-linear finite element solver allowing the user to include advanced contact modeling, various element types, material and geometrical non-linearities being a standard requirement for industrial design solutions having an overhang constraint. Several industrial applications will be demonstrated comparing the differences in structural layout and structural performance for topology optimized designs with and without manufacturing constraints [1,2].

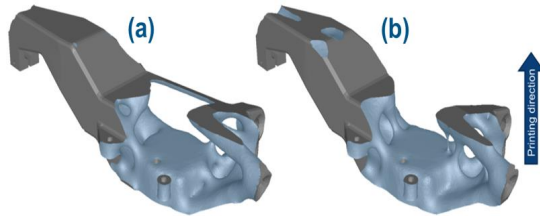


Figure 1. Design without (a) and design with (b) additive manufacturing overhang constraint.

Recently, several advances have been obtained for structural adjoint sensitivities [3,4] and implemented in solution [5] to address industrial challenges. For example designers expect a fast turnaround time when designing using topology optimization for conceptual design. The solution presented is a valuable tool for the topology optimization designer due to the highly efficient LCP (Linear Complementarity Problem) technique for solving the finite element models which include small sliding frictionless contact and preloading. Additionally, the LCP technique brings realistic simulation and thereby, realistic optimization to designers. The realistic simulation is given by the fact that the contacts of the interfaces between the different parts are included into the adjoint sensitivities calculations. A frequently applied designer approach is to tie the contacts of the interfaces between the parts often yielding incorrect topology optimization solutions as the stiffness of the interfaces are modeled having too high stiffness which the optimization algorithm will exploit. Commonly in a validation and certification process the linearly optimized design will not pass as the validation and certification process due to the incorrect treatment of the contact conditions. Using the LCP technique for the optimization increases the success of the designs in the validation and certification process due to a more realistic modeling. More importantly, the costs of redesigning late in the validation and certification process can be reduced. Secondly, it is demonstrated that realistic simulation including pre-loading of the assemble process, stiffness of the bolt connections and contacts can be included for obtaining realistic additions to the actual service-loads being applied for the optimization to achieve realistic optimization results. Thirdly, optimization using the adjoint sensitivities for design responses of finite element results including material non-linearities, geometrical non-linearities for large deformations and contact as well as of various element types such as shell elements and surface stress integrated element types will be shown.

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Optimal structures for crash by additive manufacturing

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Key Words: *Crashworthiness, Topology Optimization, Additive Manufacturing, Level Set Method*

Topology optimization (TO) allows for identification of optimal material distribution within a defined design domain and under specified boundary conditions. It has proven to be a valuable tool for design of concept structures at early stages of the product development process. However, due to complexity of the designs generated by TO methods and lack of methods to integrate manufacturing constraints, the use of TO approaches was often restricted to academic studies only. With the evolution of additive manufacturing (AM) techniques, the design freedom has significantly increased, allowing for production of parts with minimal limitations on complexity and shape. As a result, TO seems to be a perfect technique to fully exploit the capabilities of AM. Nevertheless, AM can also involve several manufacturing limitations, such as maximal overhang angle, minimal wall thickness, or cost of support structures, which should be taken into account during the optimization process. In particular, many authors attempt to address the problem of maximal overhang angle via development of methods for design of self-supporting structures that eliminate the need for additional support material and its costly removal [1, 3, 4].

This paper presents a novel method for design of self-supporting structures based on the evolutionary level set method (ELSM) [2]. Due to the generality of the proposed approach, it can be applied to different problems in structural mechanics. In this paper, we focus on a particularly complex problem, involving high noisiness and nonlinearity, which is TO of automotive structures for crashworthiness criteria. The ELSM approach uses a parametrization based on the level set method (LSM), which allows for an implicit parametrization of the material boundary. As a result, the interface between the material and void is clearly defined and the overhang angle can be easily calculated for each segment along the interface. By introducing geometric basis functions, the number of design variables can be reduced significantly and derivative-free optimizers can be applied. Design of self-supporting structures is realized through a constraint requiring the overhang angle to be lower than a specified value (typically 45°) for all downward facing faces, as suggested by Brackett et al. [1]. Small, self-supporting cavities as well as short ledges are not taken into account in the constraint.

For the evaluation of the method, an intrusion minimization problem with volume constraint for a 2D transverse bending test case is considered (Figure 1). A comparison of the structures obtained for different impact velocities with and without constraint on maximal overhang angle is shown in Table 1. The

results show that the method is very promising and could contribute to integration of AM techniques in automotive industry. Due to the flexibility of stochastic optimizers, the method can be further improved by including additive manufacturing process simulation into the optimization loop in order to account for additional criteria. Extension of the method to optimization of 3D structures is straightforward and is currently under investigation.

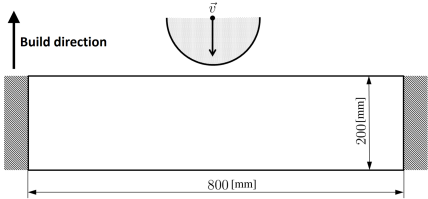


Figure 1: Design domain, initial and boundary conditions for the investigated crash case.

Impact velocity	Reference design	Best design for AM	$\frac{\text{Intrusion for AM design}}{\text{Intrusion for reference design}}$
10 [m/s]			106%
20 [m/s]			112%
40 [m/s]			116%

Table 1: Comparison of the best designs with and without constraints for additive manufacturing (45° maximal overhang angle). Intrusion minimization problem with 50% volume constraint.

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Overhang free topology optimization applied to flow optimization

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Key Words: *Topology optimization, Additive manufacturing, Overhang, Flow optimization*

Manifolds often have suboptimal fluid flow because the manifold is composed of tubes or because it is manufactured by drilling and then partially plugging holes in a solid block of metal. With topology optimization, the manifold design can be optimized for e.g. minimal pressure drop. However, the resulting complex designs often cannot be manufactured by the conventional production processes. Consequently, post-processing of the design is required to allow for clearance or tool access, compromising the optimality. Using additive manufacturing, these complex designs can be produced. However, there are also some process limitations associated with additive manufacturing that need to be accounted for.

In additive manufacturing a three-dimensional component is realized by building layer upon layer. Thus there should be sufficient support for each layer built. This limits the angle a down-facing surface can make with the base plate: the minimum overhang angle. If this angle is below the critical minimum, supports need to be added during the build, and removed after the build. For manifolds, this is especially problematic as fluid channels need to be clear of support material. Because there are typically multiple channels in a single piece, it is often impossible to orient the manifold such that all the channels are free of overhang. Therefore, an overhang constraint is used during the optimization to obtain an optimal, but printable design.

Multiple overhang constraints have been presented recently, most notably those by Gaynor and Guest [1], and Langelaar [2]. However, these constraints seem either highly non-linear [1] or mesh dependent [2]. In this study a constraint based on front propagation is used. The front propagation mimics the printing process; with every printed layer, the boundary of the product is propagated. This gives an indication for the printability of the topology, and the sensitivities of the propagation are used in the optimizer to enforce overhang-free topologies. The evaluation of the constraint and its sensitivities is computationally inexpensive, and the constraint can be applied for an arbitrary overhang angle.

Results of the overhang constraint applied to a 3D manifold optimization will be shown.

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Experimental validation of topology optimization of Additive Manufactured polymeric beams subjected to three-point bending test

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Key Words: *Topology Optimization (TO), Additive Manufacturing (AM), 3D Printing, Flexural behaviour*

Topology Optimization (TO) is a powerful tool for the optimization of product geometry and weight for compliance with structural requirements. The shapes generated by TO are generally complex and intricate, but nowadays they can be produced by Additive Manufacturing (AM) or 3D Printing [1]. 3D Printing is the term that is widely used to address layered manufacturing in the case of consumer applications with polymeric materials [2] while AM mostly refers to industrial applications. The basic algorithm for TO is based on the Solid Isotropic Material with Penalisation (SIMP) method [3].

The increasing importance of AM has recently driven researchers to develop modified versions of the SIMP algorithm [4] for considering the constraints and peculiarities of layered manufacturing, such as the use of lattice structures with intermediate densities [5] or the need to include support structures in the case of overhanging features [6]. Owing to the diffusion of AM and 3D Printing, SIMP methods have also been implemented in many commercial computer aided design and engineering (CAD/CAE) software packages. Specific TO software is also available outside CAD packages. However, the anisotropic nature of layered technologies brings additional challenges for TO methods, especially in the case of load bearing structures [7]. There is the need of improving the performances and the accuracy of TO by considering the peculiarities of the adopted AM techniques and the properties of the specific material.

In this work a commercial TO software, SolidThinking Inspire, is used to optimize the geometry of polymeric beams subjected to a three-point bending test under different loading levels. Two different AM technologies are considered to produce the beams: powder bed Selective Laser Sintering (SLS) and material extrusion 3D Printing. Several polymeric materials are used and for the specific AM process the TO calculations are defined by considering the mechanical properties declared by the supplier on the material datasheet. The results of TO are then validated by fabricating and testing replicas of the optimized beams with the corresponding material and process.

The workflow of the research is represented in Figure 1. Starting from the CAD model of a three-point bending beam with some design space for TO (Fig. 2a), the TO is then executed (Fig. 2b) with different load levels for the different materials and the optimized beam is then fabricated using the corresponding AM process (Fig. 2c). Finally, the results of the 3-point bending test performed on the replicas of the optimized beams are compared to the TO results. Correlation and differences between the experimental behaviour of the beam and the flexural resistance predicted by TO are analysed and discussed.

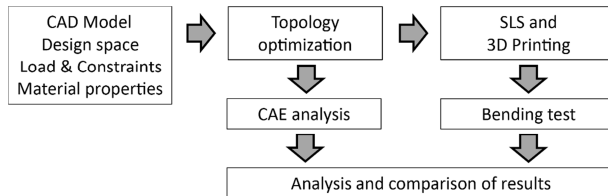


Figure 1. Workflow for experimental validation of TO results.

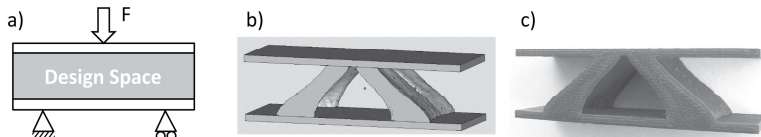


Figure 2. Model for TO of beams subjected to three-point bending test (a), optimized beam with a 70% weight reduction (b), 3D printed optimized beam in ABS for experimental testing (c).

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Linking free-form optimization to CAD-supported manufacturing

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Key Words: *Shape Optimization, Vertex-Morphing, CAD, Additive Manufacturing*

The current state of the art in shape optimization is dominated by approaches utilizing computer-aided design (CAD) or morphing boxes. On the contrary, node-based or free-form optimization approaches have not reached the same industrial acceptance. Although e.g. the Vertex Morphing Method showed with many practical applications, e.g. [1], promising characteristics like high optimization potential, minimum modeling effort or fast design space exploration. One major reason for this limited popularity is the missing link to CAD being the primary design tool and basis for manufacturing in many industrial branches. Current research at the Chair of Structural Analysis at TUM closes this gap utilizing NURBS-based mapping technologies. Hence, high quality CAD-models may be reconstructed from discrete designs obtained by free-form optimization. Assuming a CAD-based design environment, this gives rise to significantly improved design optimization workflows.

As particular example for an improved design optimization workflow, we in this work consider the linking of free-form optimization to an additive manufacturing (AM) process, which itself is part of a CAD-based design chain. Indeed, AM can also handle discrete geometry inputs as they arise in free-form shape optimization. However, having a high-quality CAD-model, instead of e.g. an STL-file of the optimized design, allows for prints with superior quality. Another advantage of such a tight link between free-form optimization and AM through CAD is, that the full potential of AM may be exploited. More precisely, Vertex Morphing allows finding shapes with almost no restrictions. This often leads to significant design improvements, but typically also increases the manufacturing effort. On the contrary, AM allows to print complex shapes without a significant scaling of the manufacturing effort. Combining both in a common design and manufacturing workflow hence yields a promising rapid prototyping process. Finally, Vertex Morphing allows to explore design alternatives without expensive reparameterization. Realizing different design solutions hence becomes very efficient, which obviously matches the idea of rapid prototyping.

The present work discusses all the above stated advantages using the example of an actual part for which the complete design workflow was realized. Focus will be set on how numerical free-form optimization in combination with CAD-reconstruction can be leveraged to obtain quality prints of promising designs. A presentation of actual 3D prints finally emphasizes the capabilities of such a combined workflow.

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GPU-Based Interactive Topology Optimization

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Key Words: *Topology Optimization, Interactive Simulation*

With appearance of new manufacturing technologies, we are able to produce more optimal designs which are cost and energy efficient. For creation of such optimal designs, often designer's intuition alone does not suffice. One possible approach is to use standard simulation tools combined with expert knowledge. However, this process is time consuming and may hinder the rapid prototyping development stage. As an alternative, Topology Optimization [2] (TO) offers mathematical computation of the optimal solution, providing the most optimal designs even to non-expert designers. Drawback of the TO tools is that they come with a high computational overhead which prevents designers from exploring solutions in 3D space interactively as in TopOpt application [1].

In this work we demonstrate the use of efficient geometric multigrid method [3] on a structured hexahedral meshes. With this strategy we can exploit the computational power of GPUs to obtain solutions nearly interactively. Reduced optimization time enables designers to make important design decisions early in the product development stage. Furthermore, for better user experience our optimization tool is integrated into a CAD system. This allows a user to input any standard CAD-format file, and perform optimization by easily choosing design space, boundary conditions, and by assigning different loads.

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Shape optimization of a layer by layer mechanical constraint for additive manufacturing

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Key Words: *Shape optimization, Additive manufacturing, Level set method*

This work introduces a new constraint functional for shape optimization problems which takes into account the construction issues related to additive manufacturing technologies [3], and notably allows to deal with *overhangs* (i.e. large regions hanging over void).

More precisely, we consider a model problem of the form [1]:

$$\min_{\Omega \in \mathcal{U}_{ad}} J(\Omega), \text{ s.t. } P(\Omega) \leq \alpha, \quad (1)$$

where the objective function $J(\Omega)$ is for instance the elastic *compliance* of structures $\Omega \subset \mathbb{R}^d$ (where $d = 2, 3$), as a measure of their robustness.

The constraint $P(\Omega)$ involves all the *intermediate* structures of Ω ,

$$\Omega_h = \Omega \cap \left\{ x = (x_1, \dots, x_d) \in \mathbb{R}^d, x_d < h \right\}$$

corresponding in the particular stages of the layer by layer construction process where the structure is assembled up to height h . More precisely,

$$P(\Omega) = \int_0^H j(u_{\Omega_h^c}) dx, \quad (2)$$

where $j : \mathbb{R}^d \rightarrow \mathbb{R}$ is a given function, and $u_{\Omega_h^c} : \Omega_h \rightarrow \mathbb{R}^d$ describes the elastic behavior of the Ω_h during the construction process (which is distinct from the elastic behavior of the end product Ω , in the situation of its final use, which is used in the evaluation of the performance $J(\Omega)$): they are clamped on the build table $\Gamma_0 \subset \partial\Omega_h$, and submitted to gravity effects, modeled by a body force $g : \mathbb{R}^d \rightarrow \mathbb{R}^d$.

We discuss practical implementations of the optimization program (1), and several numerical examples are proposed to deal with concrete problems, in two and three space dimensions. One example is depicted on Figure 1: the compliance of a 2d ‘MBB’ beam is optimized. The optimized shape without manufacturing constraint present several large overhangs of utter structural significance. The addition of our manufacturing constraint (2) prevents the appearance of such regions on the optimized shapes.

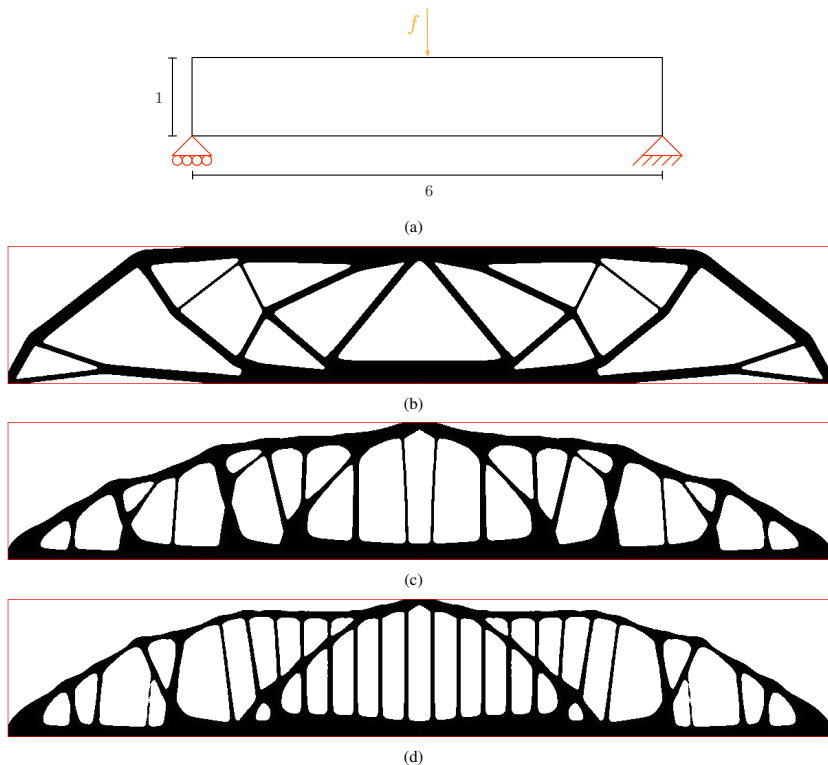


Figure 1: *Optimized shapes for the 2d MBB Beam example; (a) setting of the test-case; (b) optimized shape without manufacturing constraint; (c-d) optimized shapes for (1) using different thresholds α .*

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Large-scale three-dimensional topology optimization considering overhang limitations in 3-D printing

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Key Words: *Topology optimization, Additive manufacturing, Support structure*

Structural topology optimization procedures deal with optimizing the distribution of material within a defined volume, subjected to external loads and boundary conditions. As these methods can generate relatively complex designs, additive manufacturing (AM) technologies, and specifically 3-D printing, seem to be the perfect match for producing these shapes. Despite the great freedom that AM can provide to designers, the technology still suffers from various limitations. One of these is the maximum overhang angle, meaning that one cannot manufacture overhang patterns without additional supports. The most immediate idea to alleviate this limitation is to integrate the supports in the design – meaning generate topologies that include supporting structures and can thus be printed without additional scaffolding.

Several methods were developed recently in that spirit. Because applying explicit geometric constraints into the widespread density-based topology optimization approach can be challenging, several studies proposed a filter/projection approach. In Guest and Gaynor's work [1] as well as in Langelaar's [2], the existence of material at each point depends on whether it is properly supported in its immediate neighborhood. Both approaches report good printability and relatively minor drops in performance – in terms of structural compliance. Another approach that was presented recently by the authors relies on creating a “virtual skeleton” – essentially an optimal truss that is generated based on allowable directions only. The stiffness of the load-carrying continuum is linked to the existence of truss members by a geometric projection, thus giving preferred locations for material distribution in the continuum problem. Encouraging results were obtained in 2-D and in initial 3-D examples [3].

The current work focuses on the three-dimensional generalization of the method and on enabling the optimization of real-world aerospace components that are intended to be manufactured by SLM of Titanium alloys. 3-D topology optimization tends to lead to shell-like structures, making the extension of the virtual truss concept not trivial. We will discuss the influence of several parameters that control the truss optimization and have a significant effect on the outcome of the subsequent continuum optimization. Furthermore, we will present the capability to optimize within general design domains by means of embedding the shape and the virtual skeleton into a simple structured grid, for which large-scale topology optimization can be performed efficiently [4].

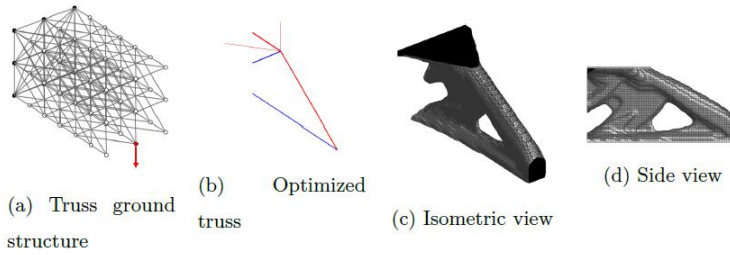


Figure 20: Topology optimization of a 3-D cantilever with a virtual skeleton for printing in the X-direction.

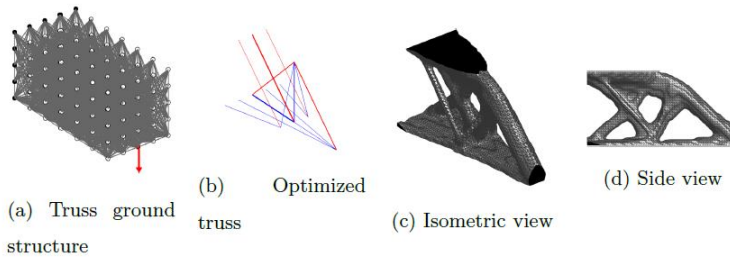


Figure 21: Topology optimization of a 3-D cantilever with a virtual skeleton for printing in the Z-direction.

The virtual skeleton approach applied to a 3-D cantilever printed in the X- and Z-directions [3]

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Shape and Topology Optimization Using CutFEM

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Key Words: *Shape and topology optimization, cut finite element method, isogeometric analysis, level set, optimal build orientation*

We present a shape and topology optimization method based on the cut finite element method, see [1], [2], and [3], for the optimal compliance problem in linear elasticity and problems involving restrictions on the stresses.

The elastic domain is defined by a level-set function, and the evolution of the domain is obtained by moving the level-set along a velocity field using a transport equation. The velocity field is defined to be the largest decreasing direction of the shape derivative that resides in a certain Hilbert space and is computed by solving an elliptic problem, associated with the bilinear form in the Hilbert space, with the shape derivative as right hand side. The velocity field may thus be viewed as the Riesz representation of the shape derivative on the chosen Hilbert space.

We thus obtain a coupled problem involving three partial differential equations: (1) the elasticity problem, (2) the elliptic problem that determines the velocity field, and (3) the transport problem for the levelset function. The elasticity problem is solved using a cut finite element method on a fixed background mesh, which completely avoids re-meshing when the domain is updated. The levelset function and the velocity field is approximated by standard conforming elements on the background mesh. We also employ higher order cut approximations including isogeometric analysis for the elasticity problem. In this case the levelset function and the velocity field are represented using linear elements on a refined mesh in order to simplify the geometric and quadrature computations on the cut elements. To obtain a stable method, stabilization terms are added in the vicinity of the cut elements at the boundary, which provides control of the variation of the solution in the vicinity of the boundary. We present numerical examples illustrating the performance of the method.

We also study an anisotropic material model that accounts for the orientation of the layers in an additive manufacturing process and by including the orientation in the optimization problem we determine the optimal choice of orientation.

We present numerical results including test problems and engineering applications in additive manufacturing.

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Taking into account thermal residual stresses in topology optimization of structures built by additive manufacturing

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Key Words: *Topology optimization, Manufacturing constraints, Thermal residual stresses*

We present a model for taking into account thermal residual stresses induced by additive manufacturing (selective laser melting process) in shape and topology optimization of structures. If we denote by Ω the final structure which is subject to optimization, the main idea (already discussed in [1]) is to introduce a sequence of intermediate shapes $\Omega_i = \{(x, y, z) \in \Omega \text{ s.t. } z \leq h_i\}$, $1 \leq i \leq n$, obtained from the previous one by adding a layer, at each stage of the fabrication process (see Figure 1), and to formulate a constraint on this collection of intermediate shapes. This constraint is evaluated thanks to a new time-dependent state equation which is composed of the heat equation and the quasi-static thermo-elasto-plastic system. We follow the lead of [3] for modelling thermal residual stresses.

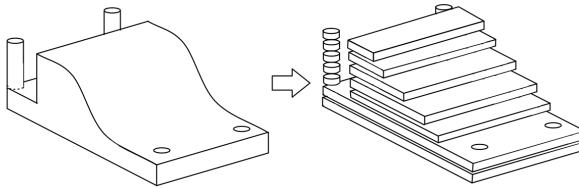


Figure 1. Slicing process yielding a sequence of intermediate shapes.

We consider a thermo-elasto-viscoplastic evolution with unknowns: the temperature T , the displacement vector field u , the plastic tensor p . The i -th layer, which is added to the intermediate shape Ω_{i-1} to obtain the new shape Ω_i , is built between times t_{i-1} and t_i , where t_0 is the initial time and t_n the final time. The equations are

- heat equation:

$$\rho \frac{\partial T}{\partial t} - \operatorname{div}(\lambda \nabla T) = Q \quad \text{in } (t_{i-1}, t_i) \times \Omega_i \quad (1)$$

- thermoelastic equilibrium equation:

$$\begin{cases} -\operatorname{div}(\sigma) = f & \text{in } (t_{i-1}, t_i) \times \Omega_i, \\ \sigma = \sigma^{el} + \sigma^{th} & \text{in } (t_{i-1}, t_i) \times \Omega_i, \\ \sigma^{el} = A(e(u) - p) & \sigma^{th} = K(T - T_{init})\mathbb{I}_n, \end{cases} \quad (2)$$

where the Cauchy stress tensor σ is the sum of the elastic stress σ^{el} and the thermal stress σ^{th} ,

- plastic flow rule

$$\frac{\partial p}{\partial t} = \frac{\sigma - P_K(\sigma)}{\beta} \quad \text{in } (t_{i-1}, t_i) \times \Omega_i \quad (3)$$

where $\beta > 0$ is the viscoplastic parameter related to the Perzyna regularization and P_K is the orthogonal projection on the convex set K given, in the case of the Von Mises criterion, by

$$P_K(\sigma) = \sigma - \max(0, 1 - \frac{\sigma_c}{|\sigma_D|})\sigma_D$$

with σ_D the deviatoric part of the stress σ and $\sigma_c > 0$ the plastic yield limit.

From this we build an objective function which is

$$J(\Omega) = \int_{\Omega} j(u_{final}) dx + \sum_{i=1}^n \int_{t_{i-1}}^{t_i} \int_{\Omega_i} k(u, T, p) dx dt$$

where (u, T, p) is the solution of (1), (2) and (3), while u_{final} is the elastic displacement for the final shape submitted to its own loads. We compute the shape derivative of $J(\Omega)$ by an adjoint method and optimal design are obtained numerically by the level set method [2].

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MPF multi-scale topology optimization to maximize heat conductivity of a metallic material assuming additive manufacturing

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Key Words: *Heat Conductivity, Metallic Crystalline Structure, Multi-phase Field Method, Multi-scale Topology Optimization, Additive Manufacturing*

It is getting real that metallic crystalline structure can be controlled to a degree in an AM process. In the meanwhile, material design to obtain an optimal microstructure applying a numerical approach is receiving a lot of attention, especially in the field of advanced materials. In this context, it is worth developing numerical method, namely optimization scheme, to improve material properties of metallic crystalline structure. For this reason, the present study challenges to develop topology optimization scheme for crystalline metals.

However, the geometry of metallic crystalline structure is complex and the conventional topology optimization is unsuitable to represent it. For this reason, the present study applies so-called the Multi-Phase Field (MPF) method which is nowadays common scheme for metallic material science. The objective is to maximize the heat conductivity of a macrostructure consisting of dual-phase crystalline metal with respect to a prescribed material volume. At this point, a multi-scale analysis must be considered to represent the hierarchical and mechanical relationships between different scales and these relationships also must be affected to the optimization algorithms. This challenging work should be of great value in the field of material science and material design and its versatile framework is introduced. The proposed method is examined by a series of numerical examples and eventually verified that it can provide a reliable optimal design for crystalline metals to maximize the heat conductivity of macrostructures.

A Virtual-Temperature-Method for Topology Optimization Design Considering Manufacturing Constraint

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Key Words: *Topology optimization, Additive Manufacturing, Manufacturing constraints, Connectivity constraint, Virtual temperature method*

Topology optimization has been regarded as a powerful design approach for determining optimal topology of a structure to obtain desired functional performances within a defined design domain. While a topology optimum design may offer an optimal performance in computational setting, it should be pointed out that the results are often complicated, impractical or unrealizable and may not be optimal from fabrication viewpoint. In order to address this question, considering manufacturing constraints in topology optimization becomes increasingly important. The authors [1,2] have proposed a topology optimization model, labeled as virtual temperature method (VTM), for describing and enforcing the desired connectivity constraint in Additive manufacturing. In this paper, this method is introduced and modified to handle the molding constraint in order to guarantee the cast-ability of topologically designed structures. In the modified method, a new virtual thermal diffusion problem is defined and the molding constraint is set to a maximum temperature constraint. The parting directions, unidirectional or multi-directional, are modeled by modifying the heat dissipation boundaries and the material properties. This method does not require an optimization process to start from a feasible initialization and can be applied almost in any topology optimization problems. Based on the proposed method, a new mirror configuration of a large-aperture space telescope is obtained and numerical analysis shows the superiority of the new mirror configuration compared to two classical mirrors.

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On Smoother Based on Laplacian Method for Uneven Surface Derived from 3-D Topology Optimization of Electrical Machinery in Magnetic Field System

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Key Words: *Electrical machine, smoothing technique, topology optimization*

I. Introduction

Topology optimization is one of powerful numerical tools for conceptually designing the electrical machinery. It is well known that the degree of freedom of the structure is much higher than that of shape optimization. Therefore, there is a possibility that completely new structure would be discovered.

Because the converged structure derived from 3-D topology optimization is occasionally complex [1] even in the field of electromagnetics, it is difficult to practically mold 3-D optimized result. Recently, 3-D printer is capable of making the practical molding of the complex structure arising in topology optimization more familiar. However, the molded structure from 3-D printer has the uneven surface which is caused in the stage of topology optimization. Owing to uneven surface, the singular magnetic flux density would distribute on the surface.

In this paper, to smooth uneven surface of optimized result, a smoothing method using the information of STereoLithography (STL) is proposed. The proposed method, which is based on Laplacian smoothing [2], can mitigate the protrusion of vertex in optimized structure using the coordinate of center of gravity in adjacent element. Consequently, it can be seen that the degree of smoothness is advanced by 3-D molding result derived from 3-D printer.

II. Modelling of 3-D Topology and Optimization Problem

In this paper, the nonlinear reluctivity $\nu(\Psi, \mathbf{B}^2)$ in the design domain, which is the function of both constrained level set function Ψ and square of magnetic flux density \mathbf{B} , is defined by smoothed Heaviside function $H(\Psi)$ using quantic polynomial as follows:

$$\nu(\Psi, \mathbf{B}^2) = \{1 - H(\Psi)\} \nu_0 + H(\Psi) \nu_c(\mathbf{B}^2), \quad (1)$$

where ν_0 is the reluctivity in vacuum, and $\nu_c(\mathbf{B}^2)$ is the nonlinear magnetic reluctivity of iron core.

Fig. 1 shows the four poles interior permanent magnet (IPM) motor [3]. The design goal of this model is to maximize the average torque under the condition that the volume of magnetic body in

design domain Ω_d is kept less than the specified value. Fig. 2 shows the initial topology and optimized result. To increase the flux to stator core, the rotor core is higher than initial structure.

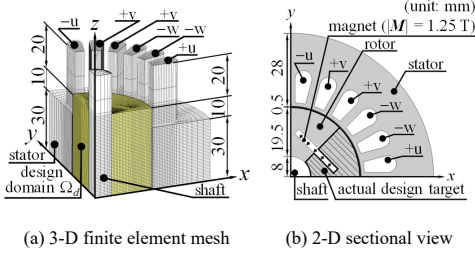


Fig. 1. IPM motor.

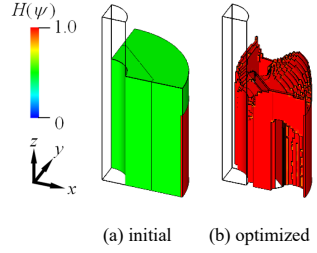


Fig. 2. Result of topology optimization.

III. Smoothing Uneven Surface of Optimized Structure

Normally, applying topology optimization, the uneven surface would be generated as shown in Fig. 2 (b). Then, the smoother based on Laplacian smoothing [2] is set up using the center coordinates of gravity of adjacent STL element. The update formula of smoother is shown as:

$$\mathbf{x}_i^{(k+1)} = \frac{\mathbf{x}_i^{(k)} + \sum_{j \in Adj(i)} \mathbf{x}_{j,i}^{(k)}}{N + 1}, \quad (2)$$

where index k shows the iteration number during smoothing process, \mathbf{x}_i is the coordinate of target node, $\mathbf{x}_{j,i}$ is the coordinate of adjacent node j , and N is the number of adjacent nodes around node i . Fig. 4 shows the result of smoothing and its 3-D printing. Because smoothing with five iterations is applied to Fig. 2 (b), the unevenness of surface is removed as shown in Fig. 4 (b). Further, proposed method will comprise keeping the electromagnetic performance during smoothing in the full paper.

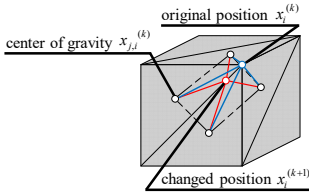


Fig. 3. Smoothing of uneven surface.

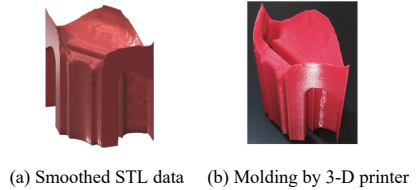


Fig. 4. Results of smoothing and 3-D printing.

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Shape optimization by a level set method of the supports in the additive manufacturing process.

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Key Words: *Mechanical and thermal supports, Shape optimization, Level set method*

Due to the Additive Manufacturing (AM), in which the objects are built layer by layer, support structures are required to support the overhangs during the building AM process (see [1] for the shape optimization of a self weight layer by layer AM process). On the other hand, support structures are highly undesirable because they increase the build time and the fabrication cost, they produce negative effects on the surface of the final built form and during the post processing, due to the complexity of the built structures, it is not possible to access and remove all the supports. Therefore, the required amount of support structures should be carefully optimized.

In this talk we discuss the shape optimization of the support structures. More precisely, we suppose that the final form is known a priori and only the shape of the support material is optimized under the weight of the overhangs or (and) the thermal constraints. Firstly, the support is modeled as a linear elastic material. Secondly, to take into consideration the thermal effects of the support, it is considered as a linear thermo-elastic material in which the thermal expansion is governed by the heat equation.

The shape derivative is computed by an adjoint method and the adjoint problem involves a backward heat equation coupled with an adjoint thermomechanical equation following the approach in [2]. The optimal shape is tracked by a level set algorithm [3]. We illustrate our results by several numerical simulations.

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Large-scale finite element analysis suitable for additive manufacturing simulation models including many multi-point constraints

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Key Words: *Finite Element Method, Multi-point Constraints, Explicit Elimination*

Sheet lamination process is one of a additive manufacturing process that create a laminated layer by cutting the contours of the layer [2]. Our final objective is to simulate the transient state of the sheet lamination process of a electric circuit board by taking into account the heat conductivity. As a first step, we have started to perform the steady state simulation based on finite element method.

As a modeling method for finite element analysis of structures created by sheet lamination process, we consider to add multi-point constraint (MPC) between each sheets [1]. The problem with the MPC conditions is a constrained minimization problem. As representative methods for solving the constrained minimization problem, the Lagrange multiplier method, the penalty method, and the explicit elimination method can be employed.

In the Lagrange multiplier method, although a solution that strictly satisfies the constraint conditions can be obtained, the matrix becomes an indefiniteness. The Penalty method obtains a solution that approximately satisfies the constraint conditions. However, when the penalty number increases to obtain high accuracy, the the matrix becomes an ill-conditioned matrix. In the explicit elimination method, a solution that strictly satisfies the constraint condition is obtained, and the matrix is a positive definiteness.

In this research, to solving large-scale problems in parallel, a iterative method is used as a linear equation solver. Additionally, we employ the explicit elimination method from the view point of that the coefficient matrix becomes positive definite and the condition number of the matrix does not become large [3].

Since the analysis model is a laminated sheet shape, the number of added MPC conditions becomes large. Therefore, it takes a lot of computation time to add the MPC conditions. In this study, to reduce the computation time to determine the MPC conditions, a bucket search is employed.

This method is evaluated by a numerical example of a large-scale model simulating a laminated printed circuit board. Table 1 shows the number of nodes, the number of elements, the degree of freedom and the number of MPC conditions in numerical example.

Table 1: Specification of numerical example

number of nodes	79,590,395
number of finite elements	60,187,328
number of degrees of freedom	238,771,185
number of MPC conditions	17,938,628

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A shape morphing technique for continuous variation of microstructures in multiscale structural topology optimization

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Key Words: *Level Set Method, Topology Optimization, Architected Materials, Shape Interpolation*

Additive manufacturing technologies make it possible to produce structures with topology at unprecedentedly small length scales. This gives opportunities to develop materials with tailored microscale architecture to achieve desired properties including those that are unattainable from natural materials. In order to exploit these opportunities, simultaneous/integrated material and structural optimization methods and concurrent multiscale topology optimization methods have been developed in recent years to design for a range of length scales [3, 7, 4]. They optimize both micro- and macroscopic topologies coupled via homogenization. The use of homogenization means periodic boundary conditions are assumed and this can lead to microstructures being discontinuous at the interfaces where there is a spatial variation of microstructures in a structure [5]. This is a problem of interest in recent years as studied by other researchers, e.g. [1, 6].

This paper aims to address the microstructure connectivity challenge. It will be embedded into the level-set based multiscale topology optimization that has been introduced by our group [2, 4], and the interface connectivity is treated as post-processing of the two geometries or objects. Manipulating an object and producing a set of intermediate objects that continuously morphs to the target object is known as shape metamorphosis in computer graphics, and many methods have been developed with many successful applications, e.g. computer animation and medical image visualization. The metamorphosis is expressed as a process where the source object deforms to match the target object. In the present study, the process is featured as an optimization problem to minimize the difference between the current and the target objects iteratively. However, existing shape metamorphosis techniques are not directly applicable for our problem as they move continuously from the source to the target objects over time. In the context of multiscale topology optimization, the source microstructure needs to be spatially morphed to the target microstructure with a strict requirement on connectivity between adjacent objects. We use shape metamorphosis to create a set of images between the two microstructures which essentially fills the interface region as shown in Figure 1c. As the level set method is employed for multiscale topology optimization, the shape metamorphosis formulation also employs the level set method, which mimics

the surface movements as a change in the distance field. Hence, a well-founded mathematical structures leads to a set of procedures that describes how pixel or voxel values can be manipulated to create in-between microstructures that are represented as a sequence of areas for 2D microstructures or volumes for 3D microstructures. The preliminary result of Figure 1 indicates that the proposed method is able to produce smoothly connected microstructures. The presentation will outline the details of the interface post-processor using shape metamorphosis and a range of numerical examples.

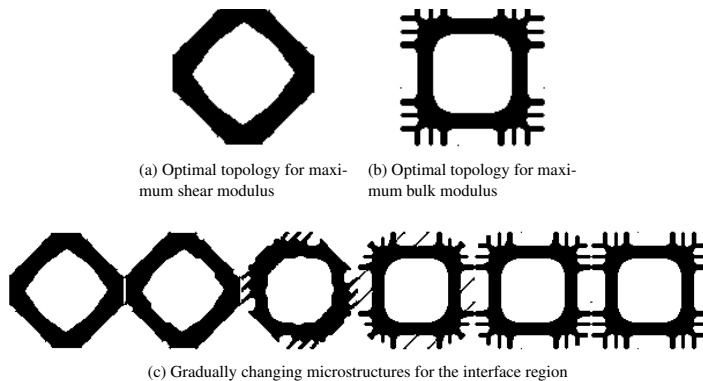


Figure 1: Example to illustrate the shape interpolation scheme

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